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APPLICATION OF WEAR COATINGS TO GUN BARRELS

John A. Bloom

Gene F. Wakefield

Texas Instruments Incorporated

TECHNICAL REPORT AFML-TR-71-254

March 1972

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Fabrication Branch
Manufacturing Technology Division
Air Force Materials Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

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APPLICATION OF WEAR COATINGS
TO GUN BARRELS

John A. Bloom
Gene F. Wakefield

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FOREWORD

This Final Technical Report covers all work under Contract F33615-70-C-1441 during the period of 16 February 1970 through 15 October 1971. The report was submitted by the authors for approval in November 1971.

The contract with Texas Instruments Incorporated, Dallas, Texas, was initiated under Manufacturing Methods Project 485-9, "Application of Wear Coatings to Gun Barrels." This work was administered under the technical direction of John R. Williamson of the Manufacturing Technology Division (LTP), Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

The program was directed by Dr. Gene Wakefield, Program Manager/Principal Investigator and was conducted by John A. Bloom, Project Engineer. This report has been given Texas Instruments internal number 04-71-11.

This program has been accomplished as part of the Air Force Manufacturing Methods Program, the primary objective of which is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in economical production of USAF materials and components.

Your comments are solicited on the potential utilization of the information contained herein as applied to your present and/or future production programs. Suggestions concerning additional manufacturing method development required on this or other subjects will be appreciated.

This technical report has been reviewed and is approved.

Henry A. Johnson

HENRY A. JOHNSON
Chief, Metals Branch
Manufacturing Technology Division

ABSTRACT

This program was undertaken to contribute to improvement in the life of rapid fire machine gun barrels by manufacturing composite barrels by lining steel barrels with a refractory carbide material. The liner was applied by chemical vapor deposition of the coating on the barrel inside diameter. Two systems, low and high temperature, were used for the depositions. Both yielded high quality titanium carbonitride liners which had good adherence and controlled thickness. Controlled firing tests showed that the performance of barrels lined by the low temperature method was less satisfactory than that of standard chromium plated barrels. Post-firing analysis indicated that the substrate metallurgical condition allowed the steel to soften at operational temperatures and caused early failure of the barrels. The liner itself appeared relatively unchanged during the tests. The performance of barrels lined by the higher temperature method was comparable to that of standard barrels. It was concluded that although the titanium carbonitride liner material offered surface protection, base materials with improved high temperature capability will also be required to achieve longer lifetimes for barrels.

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SECTION I
SUMMARY

The objective of this program was to contribute to the critical material area of developing an improved gun barrel component through the application of a wear-resistant coating to the ID of the barrel. The approach was to evaluate a hard, erosion-resistant, refractory coating applied to gun barrel inside diameters, with changes in barrel lifetime to be determined through laboratory and firing tests. The test vehicle chosen for the program was the 7.62 Minigun machine gun barrel with Texas Instruments titanium carbonitride coating. The performance goal was to double the velocity lifetime of barrels in test firing. The results of these studies and a cost effectiveness analysis formed the basis for determining the merit of constructing and demonstrating a pilot production unit.

The goals of Phase I of this program were to demonstrate (a) the utility of a hard material such as titanium carbonitride in the gun tube environment, (b) the feasibility of production, and (c) the value of an improved barrel component. Phase I was planned to provide the basis for a Production Engineering Methods program in Phase II, to produce coated barrels on a pilot production scale.

Attainment of the program goals was to be determined through actual test based on increased lifetime performance and evaluation of microstructural and metallurgical properties.

In Phase I the relative merits of two different chemical systems for this application were determined. At the end of the first six months of the program the status of both systems was to be evaluated and the system identified which showed more promise of development for maximum performance in the remaining program time period.

These systems deposit the same coating material (titanium carbonitride), but they differ substantially in the optimum deposition temperature for achieving the desired coating properties. In the higher temperature system,

good coating-to-substrate adhesion could be readily achieved. However, the coated substrate strength and structure could be degraded because of the relatively high deposition temperature, and barrel warpage or coating fractures could result from size changes. It was believed that the lower temperature approach would provide proper post-coating substrate strength and structure, but that acceptable coating-to-substrate adhesion might prove difficult to achieve because of the low deposition temperature. At the end of the first six months of the program the extent of progress and the promise of success showed by both systems was such that the program plan was changed to include both systems in the test firing.

Barrels coated by both processes were test fired. Low temperature coated barrels were reported to have performed less well than chromium-plated barrels, and high temperature coated barrels were reported to have been nominally equivalent to chromium-plated barrels. A post-coating analysis of the low temperature process barrels indicated that improper substrate structure caused significant softening of the substrate material under testing conditions. This effect was most pronounced at the substrate surface and left the substrate material malleable and easily moved by thermal and mechanical stresses. Such movement would cause coating cracks and, in severe cases, coating loss, leading to early barrel failure. High temperature coated barrels have not been subjected to post-firing analysis.

SECTION II

INTRODUCTION

A. Background

1. Erosion of Gun Barrels

Gun barrel bores deteriorate from mechanical, chemical, and thermal stresses resulting from rapid firing. The mechanism of deterioration includes the embrittlement of the surface layers of the bore by reaction with hydrogen, nitrogen, and carbon at the elevated pressure and temperature during propellant combustion. High pressures cause compression and hoop tension stresses in the gun barrel tube. High differential temperatures cause uneven thermal expansion between the thin surface layer and the depth of the metal. The ultimate result is crack formation, crack propagation, and crack intersection.

After a number of rounds, friction between the bore surface and the passing projectile induces shear stresses large enough to remove small fragments of the surface enclosed by pairs of intersecting surface cracks. The particle may redeposit at the edge of a land along the bore together with copper from the projectile and thus contribute to further erosion.

Chromium plating on gun barrels increases gun barrel life by providing a hard bore surface. Cracks in the plating allow hot combustion gases to react with the substrate gun metal and thus ultimately permit deterioration similar to that found in unplated barrels.

2. Appearance of Barrels Failed in Service

Barrels which had reached the failure point in service were examined at Texas Instruments for evidence of failure modes. Photomicrosections of the chamber from such a barrel are shown in Figures 1 through 3. In the cross section (6.5X magnification) showing the complete ID of the barrel, cracks extend radially from the interior, with deeper cracks found at the base of the lands.

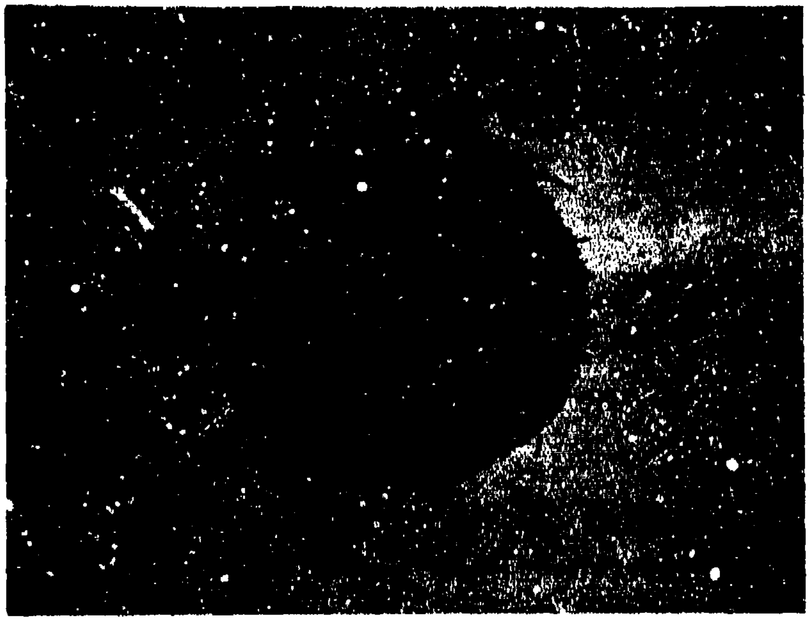


Figure 1   Cross Section of Barrel Failed in Actual Service (6.5X)

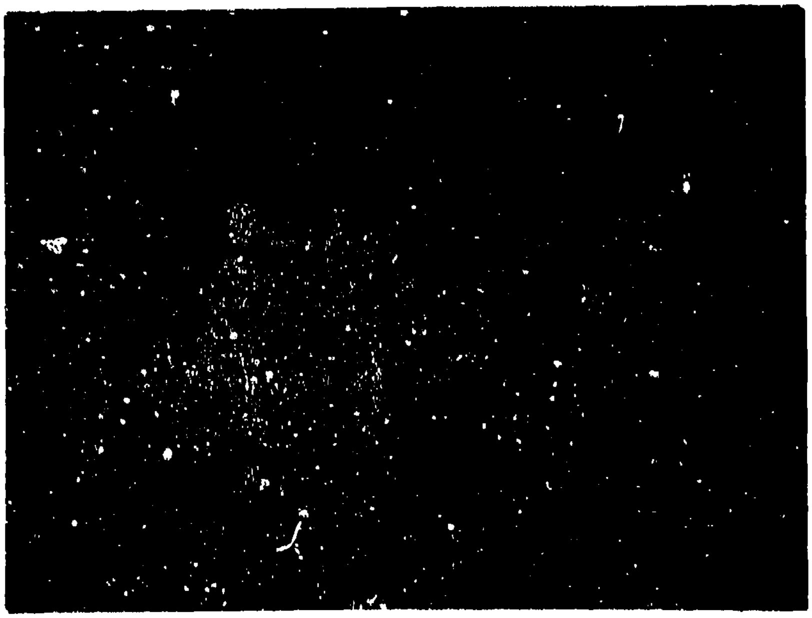


Figure 2   Cross Section from Above Barrel Showing Pullout Chromium and Steel on Left and Similar Pullout on Right Filled with Gilding Metal (100X)

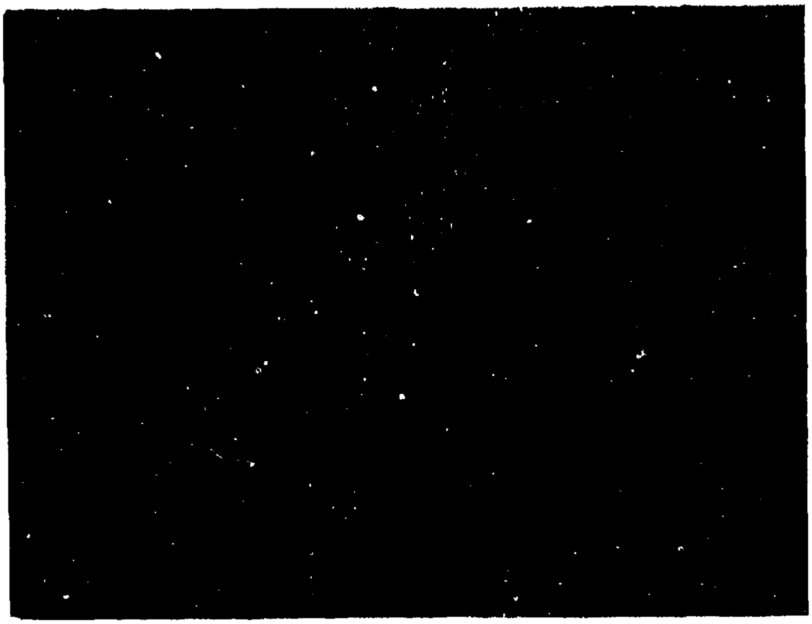


Figure 3 Higher Magnification View of Gilding Metal Extruded Into Pullout in Barrel (500X)

Figure 3, a photomicrograph of a section of the same barrel shown in Figure 1, illustrates the loss of chromium plating and a portion of the barrel, and the subsequent embedding of bullet jacket material in the cavity. Figure 4 shows an electron emission micrograph of the same area of the barrel. For such chunks of the barrel to have been extracted, it is likely that welding to the projectile itself occurred. This suggests that a material which would not readily form a bond to the soft gilding metal, or a material which forms a stable, nonvolatile, hard, refractory oxide as a coating liner, would have lower probability of galling or welding to the projectile. A material which is completely incompatible with the gilding material (for instance, aluminum oxide) might have more wear resistance than metallic coatings, such as chromium or tungsten; however, aluminum oxide materials would be very susceptible to shattering from mechanical impact. Titanium carbonitride has little tendency to weld to metals and has some impact resistance.

Figure 5 is a photomicrograph of a cross section through the corner of one of the lands of a barrel which was chromium plated and then coated with titanium carbonitride. The chromium underlayer shows porosity which could lead to gas penetration. The carbonitride coating on the chromium, which is continuous and nonporous, has partially filled the pores in the chromium.

3. Preliminary Experimentation and Testing

To screen the potential of titanium carbonitride to improve the performance of rapid-fire gun barrels, barrels without chromium plating were obtained and the carbonitride was plated directly onto the steel of the barrel using an adapted laboratory reactor system. Since the barrels were from 7.62 mm barrel production contracts, the application of a thin coating made the inside diameter undersized. Three barrels were consumed in metallurgical analysis and three were shipped to Warner-Robbins Air Force Base for test firing.

From a technical standpoint, these barrels represented strictly an initial, laboratory approach to the coating process. The process was not optimized for barrel production; there was no taper in the coating from chamber to muzzle, and the coating was not applied to barrels having polished rifling.

Figure 4 Electron Emission of Metal Extruded Into Pullout Showing Metal to be Primarily Copper (400X)

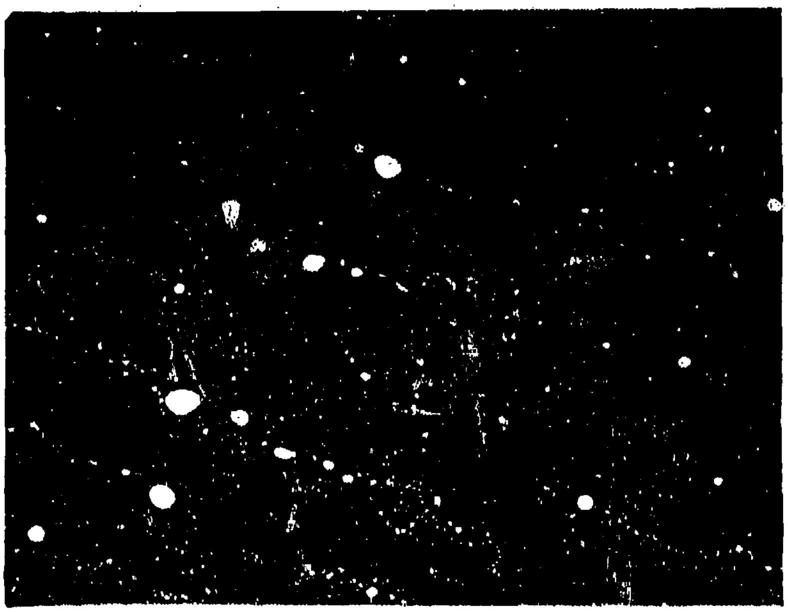


Figure 5 Cross Section of Corner of Chromium-Plated Rifle Land Showing Porosity of Chromium Plate (1000X)

The barrels were subjected to firing as part of a six-barrel set at the Naval Weapons Laboratory in Dahlgren, Virginia. Firing tests were conducted using a 7.62 mm Minigun installed on a rigid test stand and assembled with four standard and two coated barrels. The test schedule consisted of firing 500-round bursts at a 6000 RPM rate using 7.62 ball ammunition (Lot TWL 18478). Two-minute cooling periods were observed between bursts, with complete cooling every 4000 rounds. Initially and at the end of each 4000 round cycle, single round muzzle velocities were recorded for each barrel and a dispersion pattern (1000 inches from muzzle) was obtained to determine projectile yaw. Firing continued until unsatisfactory ballistic data (yaw in excess of 15° or a 200 ft/sec velocity drop) were obtained.

Velocity changes for these six barrels are summarized in Table I. Only Barrel A had reached a defined failure at the conclusion of the test. The test results indicated that the initial, nonoptimized carbonitride coated barrels were nominally equivalent to chromium-plated barrels produced by a highly developed, mature process.

The velocity data points from the test firing, given in Figure 6, form curves of a generally consistent shape, indicating that velocity is a reliable parameter on which to base barrel lifetime. All barrels show a slight initial rise in velocity, followed by a constant velocity from 40,000 to 100,000 rounds, indicating a stable barrel condition. Lines drawn through the points of each of the curves past 100,000 rounds show a relatively straight-line drop in velocity for all barrels. Qualitatively, the similar slope indicates similar failure modes.

In comparing the fired barrels, the interior bore surfaces were replicated by filling the barrel with an RTV silicone rubber fluid and removing the rubber after solidification. The replicates showed that in the chromium plated barrels near the chamber end the surfaces of the grooves were very rough, apparently as a result of a galling type of failure. Evidence of a normal wear situation, i.e., thinning of the chromium, was noted on the lands. Titanium carbonitride barrels had retained more of the original surface area; the surface in the grooves was

Table I

Summary of Barrel Test Data, Velocity Change

Barrel No. in Gatling	ID Plating	Δ Muzzle Velocity (Ft/Sec) *					
		Rounds					
		Start	4K	100K	104K	116K	120K
A	Titanium Carbonitride	-0-	+2	-132	-214	-265	-329
B	Titanium Carbonitride	-0-	+63	-38	-108	-93	-154
1	Chromium	-0-	-24	-38	-86		-117
2	Chromium	-0-	+5	-78	-149		-191
3	Chromium	-0-	+15	-55	-120		-181
4	Chromium	-0-	+17	-79	-146		-192

*Failure to be designated as a drop in velocity of 200 ft/sec from the initial velocity

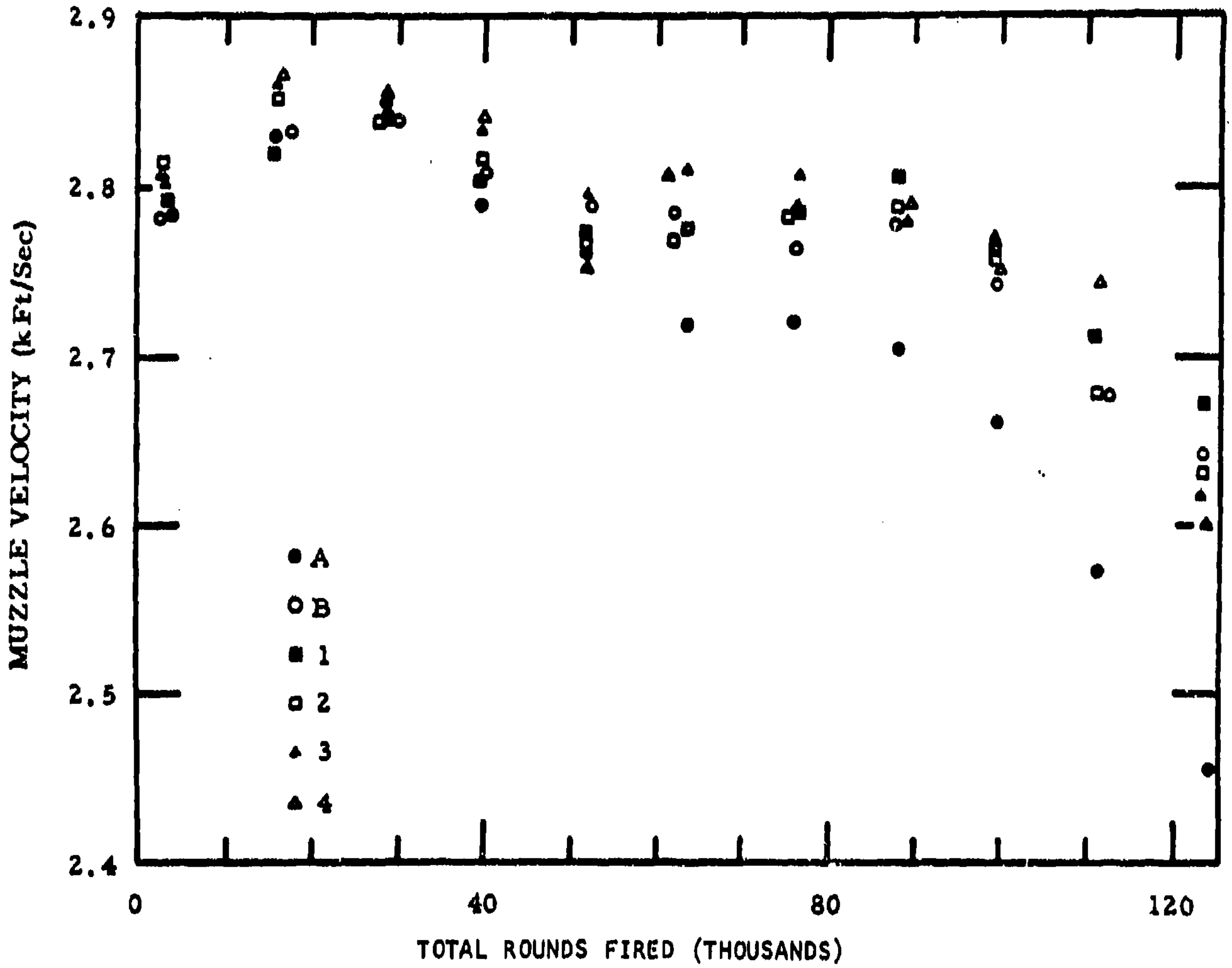


Figure 6 Velocity vs Rounds for Refractory Coated (A and B) and Chromium-Plated (1-4) Barrels

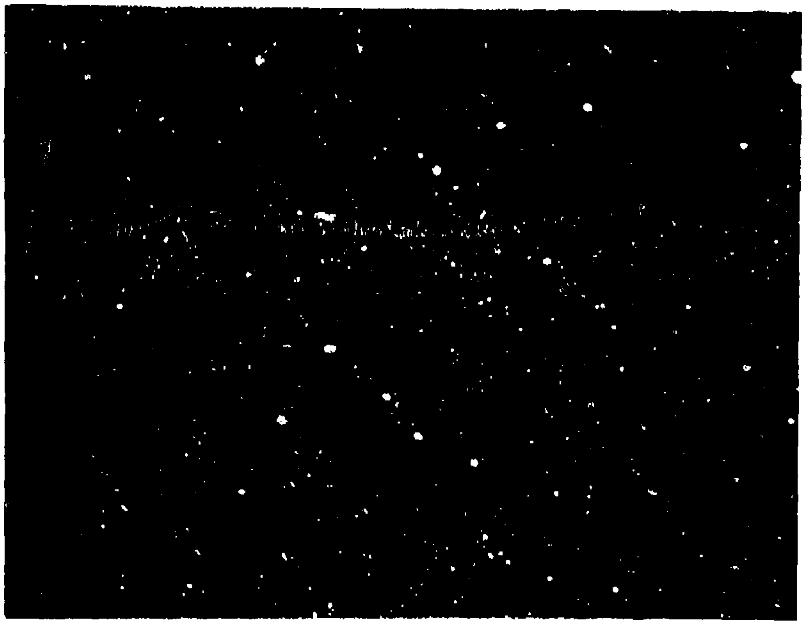
much smoother, though some areas of bare steel were noted. There was no apparent evidence of thinning or normal wearing of the carbonitride coating, which could indicate that bond failure between the thin, hard coating and the substrate material led to coating failure. The coating in these barrels was only 0.4 mil thick.

To decrease the tendency of the coating to form deep cracks at the base of the lands, a smooth radius is usually formed at the base and on the top corners of the rifling before plating. Smoothing is accomplished by the electrochemical polish step just prior to application of the chromium. Photomicrographs in Figure 7 compare the edges of the lands of a chromium plated barrel smoothed by electrochemical polish and one from the carbonitride plated barrel representing the as-machined surface. The difference in the shapes of the lands is obvious, and the smooth curvature of the chromium barrel should translate into improved performance.

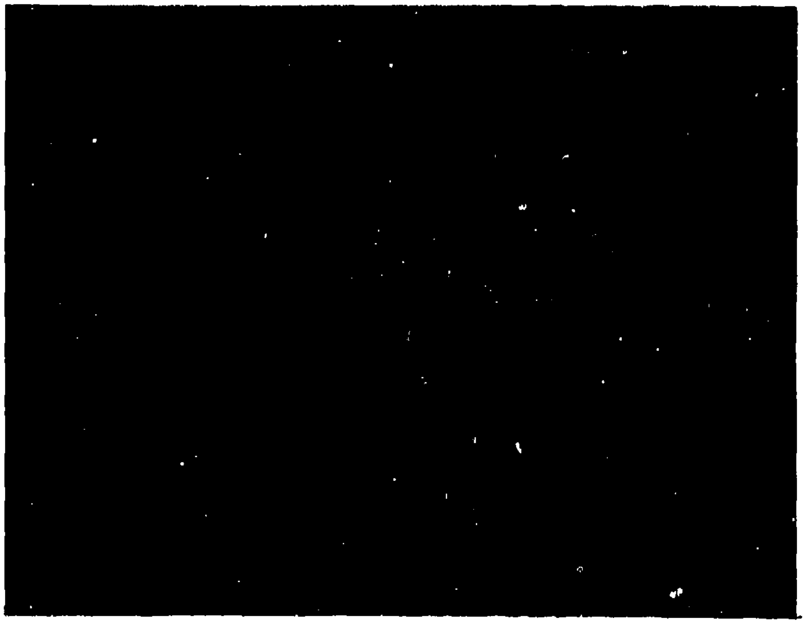
From this test firing and examination of the barrels after firing, it was concluded that a hard coating such as titanium carbonitride could improve performance of gun barrels if improvements in the coating included improved adhesion, greater coating thickness (probably 1.0 mil minimum), and a smooth radius formed on lands such as those currently found in chromium-plated barrels for better stress distribution in service.

B. Program Approach

The purposes of Phase I of the program were to demonstrate a coating process for application of titanium carbonitride coatings on machine gun barrels, to performance-test coated barrels, and to perform an economic value analysis of coated gun barrels. The carbonitride coatings, made by two different processes, were optimized on a laboratory scale and evaluated for coating of 7.62 mm gun barrels. The coating method designated "System A" utilized the present carbonitride production reaction system, and "System B" utilized a lower temperature laboratory system to coat small parts.



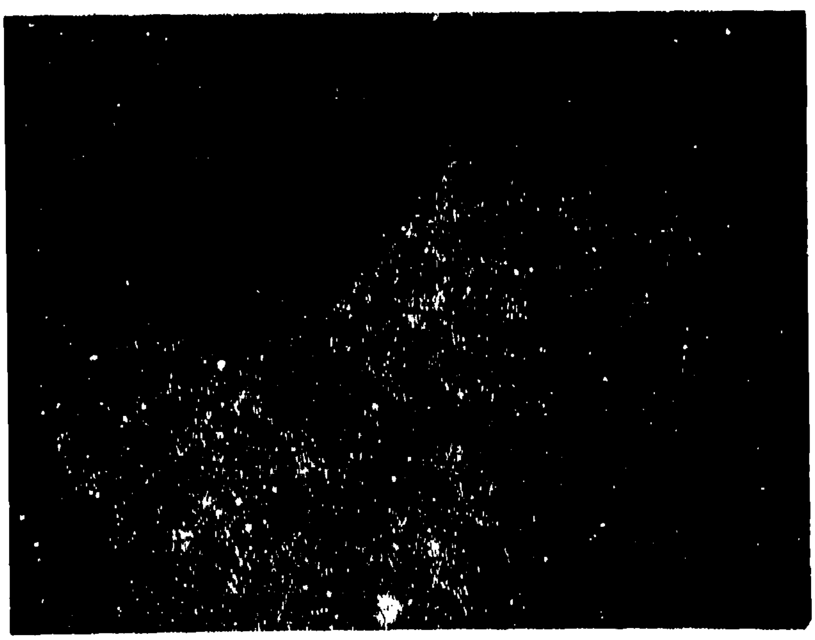
(a) Chromium-Plated Rifling (50X)



(b) Chromium-Plated Rifling (250X)

Figure 7 Comparison of the Shape of Rifling in Chromium Plated [(a) and (b)] and Titanium Carbonitride Coated [(c) and (d)] Barrel Sections

(c) Titanium Carbonitride Coated Rifling (50X)



(d) Titanium Carbonitride Coated Rifling (250X)

Figure 7 (continued) Comparison of the Shape of Rifling in Chromium Plated [(a) and (b)] and Titanium Carbonitride Coated [(c) and (d)] Barrel Sections

System A had the advantage of being a proven production coating system, so that there was less criticality in substrate preparation prior to coating to gain acceptable coating adhesion. It had the disadvantage, for some steel substrate materials, of requiring a higher coating temperature. The 7.62 mm barrels used for the screening test firing were coated using System A. An optimized coating of this type has the potential of advancing the state-of-the-art in gun barrel performance, particularly with such materials as TZM.

System B utilized a lower coating temperature, but the coating-to-substrate adhesion needed improvement to achieve a reliable, reproducible bond. Coating at the lower temperature was believed more compatible with many steels.

In both approaches, coating thickness and taper were controlled to obtain the most serviceable product, and the effects of post-treatment on substrate properties were noted.

Coated specimens were examined metallographically to establish coating thickness and bond to the substrate. Coating microhardness was determined using a Knoop Microhardness Tester, and the coating was abraded with 27 μm alumina on selected runs to determine its abrasion resistance. Coating continuity and surface finish of selected barrels were investigated by making silicone replications of the barrel inside diameters.

Since the laboratory examination results were inadequate to allow selection of a single process, test firing performance data were obtained on coatings from both processes. These firings were planned such that two process/thickness conditions would be tested in duplicate, with two standard chromium barrels completing the six-barrel set to provide the internal calibration point.

Barrel sets assembled in this manner would then be fired until failure, and the barrels which caused the failure would be identified. Failure was defined as a 200 ft/sec velocity drop or excessive (>20°) yaw. Information gathered from these firings, coupled with an economic analysis, will provide the major basis for a decision on pilot plant demonstration.

SECTION III
TECHNICAL DISCUSSION

A. Equipment Description

The reactor used in the low temperature process work is shown in Figure 8. The part to be coated is positioned horizontally inside a quartz tube, and a nozzle assembly is inserted through the ID of the part to the part's extreme end (from right to left in the figure). A heater assembly is positioned over the quartz tube so that the ID of the part at the nozzle tip is heated to the proper deposition temperature. This temperature is controlled by a thermocouple on the heater and may be maintained by thermocouples extending through the nozzle to the part ID or by thermocouples inserted from the exhaust end. During deposition, the nozzle and heater assemblies traverse the part being coated in such a way that the position of the nozzle relative to the heater remains constant and the part is coated sequentially. During this operation, the part is rotated about its axis to ensure an even temperature profile and random reactant gas distribution throughout the reaction zone. In this manner, all points on the part ID see the same temperature profile and gas concentrations during deposition. A "buffer" gas is inserted between the tube ID and the nozzle OD to prevent reactant gases from backing up into that area. A concentric reactant nozzle arrangement has been developed to isolate the various reactant gases from each other prior to their entry in the deposition zone. Reactant gases are controlled and appropriate temperatures recorded with the equipment shown on the lower right portion of the reactor. Effluent gases are scrubbed to meet safety and pollution requirements.

With this reactor system it is possible to deposit coatings of different, controlled thicknesses and tapers by changing the pull speed of the heater-nozzle assembly, and thus effectively changing the part residence time in the deposition zone. The reactor can be easily adapted to a variety of inside diameter sizes.

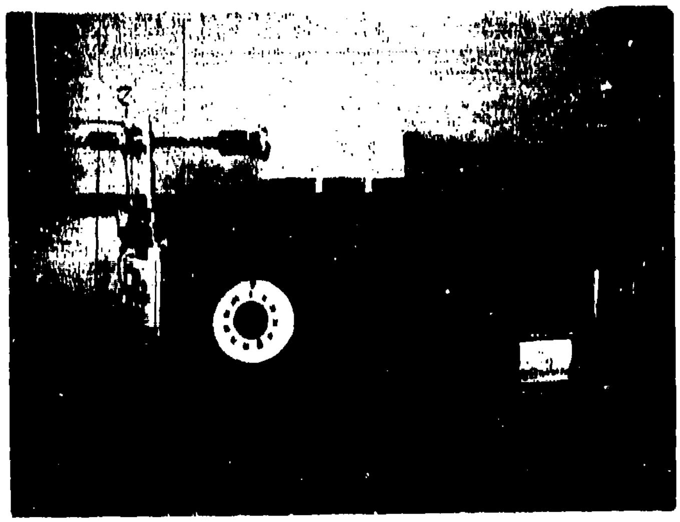


Figure 8 Low Temperature Reactor for Chemical Vapor Deposition to Inside Diameters of Tubes

The high temperature inside diameter coating reactor pictured in Figure 9 is similar in principle to the low temperature reactor. However, the barrel is positioned vertically rather than horizontally in the high temperature reactor, and the barrel traverses the nozzle and heat zone assemblies. The barrel was placed in a vertical position at the higher temperature to avoid barrel warpage. Reactant gasos enter through the bottom of the reactor and exhaust from the top while the barrel moves upward through the heater-nozzle assembly. The barrel rotates about its own axis during deposition to insure even temperature and gas distribution. As with the low temperature system, regulation of the speed of traverse allows control of deposition thickness and coating taper inside the barrel.

B. Process Optimization

1. Barrel Cleaning and Adhesion Studies

Adhesion studies of low temperature deposited titanium carbonitride on gun barrel substrate material determined the extent of adhesion problems and defined ways of solving them, as summarized in Table II. Depositions were made on small washers cut from gun barrels in a laboratory system routinely used for low temperature titanium carbonitride coatings. Coated substrate material cleaned by glass bead peening, acetone, and then methanol rinsing and drying showed little flaking*; some chipping† was observed on sharp, unfinished edges.

The preparation methods used with samples 1 and 2 gave good results. Although identical preparations were used for samples 3 and 4, the adhesion results were different. Sample 5 used only a strong descaler, Turco 4181-19, and a H_2 etch on a rough, oxidized substrate; fair adhesion was achieved, suggesting that this descaler is a good first step in the clean-up of grossly oxidized material. The results for sample 6 suggest that previous coatings should be removed before the substrate is recoated with titanium carbonitride.

* The term flaking is used to indicate separation of coating from substrate due to poor bonding.

† Chipping refers to loss of coating due to fracture caused by a high stress area. This may occur even though the bond is good.

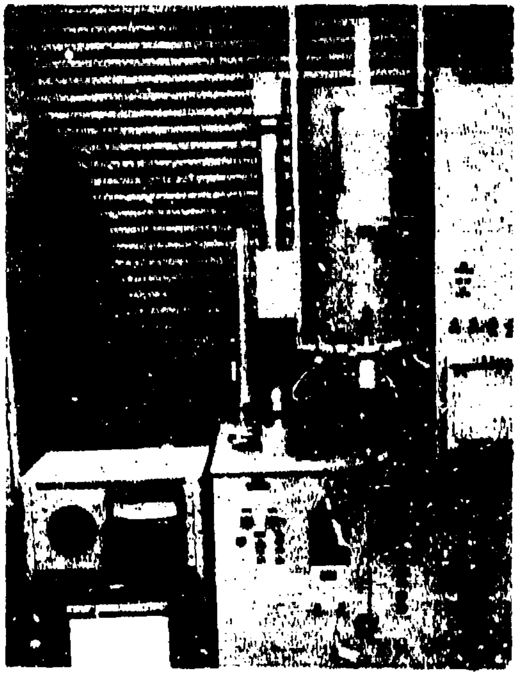


Figure 9 High Temperature Reactor for Chemical Vapor Deposition to Inside Diameters of Tubes

TABLE II

Titanium Carbonitride to Steel Adhesion Studies With Several Surface Preparations and Low Coating Temperature

Sample* Number	Piece Preparation: Sides Buffed	Alkonox Ultrasonic Degrease	50% HCl @ 55°C	H_2O & MeOH Rinse	5% Cryscoat 187 @ 55°C	Turco 4181-19 @ 90°C	H_2 Etch	Coating‡ Temperature (°C)	Results
0	Glass bead peened		X	X			X	690	Appearance quite good; some chipping.
1	X	X	X	X	X		X	696	Appeared very good; no chipping, good adherence.
2	X	X	X	X	X		X	699	Appeared very good; a small amount of chipping on rough edge
3	X	X	X	X			X	593	Poor; considerable flaking.
4	X	X	X	X			X	690	Appeared very good; a little flaking near Aquadag area.
5		X	X	X		X	X	689	Fair; some chipping and flaking.
6†		X	X	X			X	685	Fair adherence on top; poor adherence on sides.

* Mil-S-11595 Chromium-Molybdenum-Vanadium Steel

† Specimen was precoated on the outside with titanium carbonitride

‡ Temperature taken using a Thermodot TD-7 Infrared Instrument looking at Aquadag (0.93 emissivity)

Subsequent runs indicated the desirability of using HCl to clean the barrel substrate material and prepare it for coating. The barrels used in the program had previously been chromium plated and then stripped. A 15 to 30 minute treatment with an inhibited HCl etch, designed to attack any residual chromium while only slowly etching the steel, proved satisfactory for cleaning the barrels and assuring the removal of any chromium. This etch became a part of the standard barrel preparation procedure for the remainder of the contract.

The final procedure utilized in the low temperature process consisted of (1) glass bead peening of the inside of the barrel, (2) ultrasonic degreasing in Alkonox solution, (3) DI water rinse, (4) acid etch, (5) DI water rinse, and (6) isopropanol or methanol rinse and dry. As a final cleaning step, the barrels were H_2 etched at the coating temperature prior to coating.

In the high temperature process, because of the greater activity of H_2 at the higher temperature, only a trichloroethylene degrease followed by the H_2 etch at the coating temperature was necessary to obtain good coating-to-substrate adhesion.

2. Low Temperature Process Parameter Optimization

The initial scoping depositions conducted in the preliminary test runs formed the basis for a statistical series conducted to evaluate the influence of the reaction parameters on the rate and quality of coating for both the low and high temperature chemistry processes. This parameter influence optimization permitted selection of process conditions to provide coated barrels for evaluation in test firing.

The statistical plan for the low temperature process, given in Table III, was basically a two-level, four-variable experimental plan in which slightly greater than a one-half replicate was carried out. Individual experiments were run in the order listed in Table III, run numbers 1400 to 1550. From an analysis of the data, preliminary estimates of the influence of various parameters were used to calculate the expected thicknesses as given in column 10 of Table IV. This initial fit was only marginally accurate and

Table III

Low Temperature Titanium Carbonitride Run Data

Run Number	Gas Flows: Inner Nozzle (ℓ/min)	Gas Flows: Outer Nozzle (ℓ/min)	Gas Flows: Chamber Gas (ℓ/min)	Coating Thickness/Adhesion/Hardness(a) From Exhaust End: 1/2"	5"	11"	16"	21"	Pull Speed (in./hr)	Heat Zone Size (in.)	Nozzle Position Into Heat Zone (in.)	Reaction Time (min)	Average Reactor Temp. (°C)	Average Dep. Rate (mils/hr) (b)	Final Nozzle Position (in.) (c)
0930	5.43	13.32	1.1			No Mounts Made			8.5	6	1	35	700	----	17.0
0990	2.72	6.65	1.1	0.4/Fair	0.5/Good	0.5/Fair	0	0	12.0	6	1	25	687	1.20	17.0
1030	1.55	3.33	1.1	0.25/Fair	0.25/Fair	0.15/Fair	0	0	12.0	6	1	25	680	0.48	13.5
1050	4.29	1.50	1.1	0.2/Good	0.15/Poor	0	0	0	12.0	7	1	30	700	0.40	11.0
1130	4.29	1.50	1.1	0.3/Good	0.4/Fair	0.5/Poor	0.5/Poor	0.1/Poor	12.5	7	1	29	705	0.91	26.5
1140	4.29	1.50	1.1	0.4/Good	0.4/Fair	0.5/Poor	0.5/Poor	0.2/Poor	12.5	8.5	2.5	29	715	0.93	26.0
1190	5.37	3.99	1.1	0.25/Fair	0.6/Fair	0.6/Fair	0.5/Good	0.1/Fair	11.5	8.5	3.0	29	710	1.20	23.0
1210	5.37	3.99	1.1	1.3/Poor	1.5/Poor/2200	1.0/Good/2200	1.35/Good/2600	0.7/Good/2100	8.0	12.5	3.0	71	730	1.10	27.0
1260	5.37	3.99	1.1	0.5/Poor	0.7/Poor	0.95/Fair	1.05/Good	0.65/Poor	8.0	12.5	4.5	60	720	0.85	28.0
1270	5.37	3.99	1.1	0.7/Good/2500	0.95/Good/3000	0.95/Fair/1900	1.0/Good/3000	0.7/Fair/2200	9.0	12.5	3.75	59	735	0.95	29.0
1280	5.37	3.99	1.1	0.75/Good	0.9/Good	1.0/Good	0.45/Poor		8.0	12.5	3.25	69	715	0.80	19.0
1320	5.37	3.99	1.1	0.9/Fair/2100	1.2/Poor/2200	1.3/Fair/2400	1.3/Fair/2700	0.75/Good/2700	7.8	13.0	3.25	75	740	0.92	27.3
1330	3.59	2.66	1.1	0.7/Good	0.7/Good	1.15/Good	0.6/Poor		8.2	13.5	3.25	75	735	0.68	21.0
1340A	7.36	2.00	1.1	0.75/Good	0.75/Good	---	---	---	8.2	13.5	3.25	75	720	0.60	13.5
1340B	6.01	3.33	1.1	---	---	---	0.75/Good	0.7/Good	8.2	13.5	3.25	75	720	0.60	28.3

(a) mils/ /KHN$_{25}$
(b) Based on areas getting complete deposition time
(c) From exhaust end of pipe

Table III
(continued)

Low Temperature Titanium Carbonitride Run Data

Run Number	Gas Flows			Coating Thickness/Adhesion/Hardness From Exhaust End					Pull Speed (in./hr)	Heat Zone Size (in.)	Nozzle Position Into Heat Zone (in.)	Reaction Time (min)	Average Reactor Temp. (°C)	Average Dep. Rate (mils/hr)	Final Nozzle Position (in.)
	Inner Nozzle (ℓ/min)	Outer Nozzle (ℓ/min)	Chamber Gas (ℓ/min)	1/2"	5"	11"	16"	21"							
1400 A	5.37	3.99	1.1	0.95/Good	1.1/Good				7.8	13	3.25	75	740	0.80	13.5
B	5.36	3.65	1.1			1.1/Poor	1.0/Poor	0.6/Good	7.8	13	3.25	75	775	0.84	27.0
1410 A	5.36	4.99	1.1	0.75/Good	0.65/Good				7.8	13	3.25	75	705	0.56	12.75
B	5.36	4.33	1.1			0.7/Good	0.55/Good	0.375/Good	7.8	13	3.25	75	705	0.50	27.0
1450 A	5.38	4.99	1.1	1.75/Good	1.6/Fair				7.8	13	3.25	75	775	1.30	13.5
B	5.38	4.33	1.1			1.2/Poor	1.0/Fair	0.8/Fair	7.8	13	3.25	75	775	0.87	29.25
1460 A	5.38	3.65	1.1	1.4/Fair	1.35/Good				7.8	13	3.25	75	775	1.10	13.5
B	5.36	2.99	1.1			0.55/Good	0.55/Fair	0.35/Good	7.8	13	3.25	75	705	0.44	29.0
1480 A	5.38	4.33	1.1	0.8/Poor	0.75/Fair				7.8	13	3.25	75	705	0.54	13.5
B	5.37	3.99	1.1			0.9/Poor	0.8/Poor	0.6/Poor	7.8	13	3.25	75	740	0.72	26.65
1530 A	5.36	2.99	1.1	1.0/Good	1.0/Fair				7.8	13	3.25	75	775	0.80	11.0
B	5.36	3.65	1.1			0.3/Fair			7.8	13	3.25	75	705	---	22.25
1550 A	5.36	4.33	1.1	1.35/Good	1.3/Good				7.8	13	3.25	75	775	1.06	13.5
B	5.38	4.99	1.1			0.65/Good	0.5/Good	0.5/Fair	7.8	13	3.25	75	705	0.47	29.25
1610	5.36	4.33	1.1	1.3/Poor				0.9/Fair	7.8	13	3.25	75	775	1.04	30.0

Table III

(continued)

Low Temperature Titanium Carbonitride Run Data

Run Number	Gas Flow: Inner Nozzle (ℓ/min)	Gas Flow: Outer Nozzle (ℓ/min)	Gas Flow: Chamber Gas (ℓ/min)	Coating Thickness/Adhesion/Hardness From Exhaust End: 1/2"	5"	11"	16"	21"	Pull Speed (in./hr)	Heat Zone Size (in.)	Nozzle Position Into Heat Zone (in.)	Reaction Time (min)	Average Reactor Temp. (°C)	Average Dep. Rate (mils/hr)	Final Nozzle Position (in.)
1680	5.37	4.33	1.1	1.6/Good	1.5/Good	1.6/Good	1.5/Good	1.0/Good	7.8	13	3.25	75	775	1.20	31.0
1700	5.37	4.33	1.1	Fair to poor adhesion - no mounts					7.8	13	3.25	75	775		24.5
1740	5.37	4.33	1.1	1.25/Good	1.2/Good	1.8/Fair	1.75/Poor		7.8	13	3.25	75	775	1.04	29.0
1760	5.37	4.33	1.1	1.3/Fair	1.35/Fair	1.2/Fair	1.5/Poor	1.1/Poor	8.9	13	2.25	72	775	1.08	30.0
1800	5.37	4.33	1.1	1.2/Fair	1.0/Fair	0.8/Fair	0.8/Poor	0.7/Poor	11.2	13	2.25	58	775	0.83	31.0
1810	5.37	4.33	1.1	1.3/Poor/56(d)	1.3/Poor/56(d)	1.1/Poor/58(d)	1.1/Poor/57(d)	0.8/Good/57(d)	9.6	13	2.25	67	755	0.99	30.0
1820	5.37	4.33	1.1	1/3/Fair/57(d)	1.3/Fair/57(d)	1.1/Fair/58(d)	0.8/Poor/58(d)	0.5/Poor/58(d)	9.6	13	2.25	67	735	0.80	31.25
1880	5.37	4.33	1.1	1.5/Fair	1.5/Fair	1.1/Fair	0.8/Poor	0.8/Poor	10.8	13	2.25	60	755	1.15	31.0
1900	5.37	4.33	1.1	1.3/Good/57(d)	1.2/Good/57(d)	1.1/Good/57(d)	1.0/Good/57(d)	0.8/Good/68(d)	10.8	13	3.25	54	755	1.16	3[illegible].6
1940	5.37	4.33	1.1	2.2/Good	1.9/Good	2.2/Good	1.6/Good	0.9/Good	5.83	13	3.25	100	755	1.05	30.6
1960	5.37	4.33	1.1	2.0/Good	1.3/Good	1.6/Fair	1.3/Good	0.4/Good	6.25	13	3.25	94	755	1.02	24.5
1980	5.37	4.33	1.1	2.1/Good	2.2/Good	1.7/Poor	1.2/Poor	0.6/Good	5.7	13	3.25	103	755	100	24.0
2020	5.37	4.3	1.1	2.1/Poor	2.0/Poor	1.8/Poor	1.5/Poor	1.0/Good	5.7	13	3.25	103	755	100	31.0
2080	5.37	4.33	1.1	2.0/Fair	1.8/Fair	1.9/Fair	2.0/Good	1.7/Good	5.7	13	3.25	103	755	1.08	31.0
2100	5.37	4.33	1.1	1.0/Good	0.9/Fair	0.95/Good	0.8/Fair	0.8/Good	10.8	13	3.25	54	755	1.00	31.0
2120	4.33	5.37	1.1	0.95/Good	0.8/Good	0.8/Fair	0.6/Good	0.5/Good	10.8	13	3.25	54	755	0.83	31.0
2170	5.37	4.33	1.1	2.5/Good	2.0/Good	2.0/Good	1.5/Good	1.0/Good	5.5	13	3.25	106	755	1.00	31.0
2220	5.37	4.33	1.1	1.2/Good	1.1/Good	0.8/Good	0.8/Good	0.7/Good	10.8	13	3.25	54	755	1.00	31.0
2240	5.37	4.33	1.1	2.1/Good	2.0/Good	1.9/Fair	1.5/Good	1.0/Good	5.7	13	3.25	104	755	0.98	31.0

(d)Substrate (R_A)

Table III

(continued)

Low Temperature Titanium Carbonitride Run Data

Run Number	Gas Flows: Inner Nozzle (ℓ/min)	Gas Flows: Outer Nozzle (ℓ/min)	Gas Flows: Chamber Gas (ℓ/min)	Coating Thickness/Adhesion From Exhaust End: 1/2"	5"	16"	19"	21"	Pull Speed (in./hr)	Heat Zone Size (in.)	Nozzle Position Into Heat Zone (in.)	Reaction Time (min)	Average Reactor Temp (°C)	Average Dep. Rate (mils/hr)	Final Nozzle Position (in.)
2290	5.36	4.33	1.1	/good	/good	/fair	/good	/fair	10.6	13	3.25	55	755	---	31.0
2310	5.36	4.33	1.1	1.2/good	1.2/good	1.2/good	0.9/good	0.5/fair	10.6	13	3.25	55	765	---	31.0
2330	5.36	4.33	1.1	2.0/poor	2.2/poor	0	0	0	5.7	13	2.75	109	765	1.15	13.0
2370	5.36	4.33	1.1	1.4/poor	1.8/poor	0	0	0	5.7	13	3.75	98	765	0.98	11.0
2440	5.36	4.33	1.1	/good	/good	/good	/good	/fair	5.7	13	3.25	104	755	---	31.0
2460	5.36	4.33	1.1	/good	/good	/good	/good	/good	5.7	13	3.25	104	755	---	31.0
2510	5.36	4.33	1.1	/good	/good	/good	/good	/good	10.6	13	3.25	55	755	---	31.0
2530	5.36	4.33	1.1	2.1/good	2.0/good	1.7/fair	1.5/fair	1.0/fair	5.7	13	3.25	104	755	---	31.0
2570	5.36	4.33	1.1	/good	/good	/good	/good	/good	10.6	13	3.25	55	755	---	31.0

Table III
(continued)

Low Temperature Titanium Carbonitride Run Data

Run Number	Gas Flows: Inner Nozzle (ℓ/min)	Gas Flows: Outer Nozzle (ℓ/min)	Gas Flows: Chamber Gas (ℓ/min)	Coating Thickness/Adhesion From Exhaust End: 1/2"	5"	11"	16"	21"	Pull Speed (in./hr)	Heat Zone Size (in.)	Nozzle Position Into Heat Zone (in.)	Reaction Time (min)	Average Reactor Temp. (°C)	Average Dep. Rate (mils/hr)	Final Nozzle Position (in.)
2590	5.36	4.33	1.1	0.95/Good	1.7/Good	1.7/Good	1.8/Good	0.7/Good	6.0	13.0	3.25	97	755	0.93	31.0
2650	5.36	4.33	1.1	1.8/Poor	1.75/Poor	1.85/Good	1.55/Good	0.45/Good	5.5	13.0	3.25	106	755	0.96	31.0
2710	5.36	4.33	1.1	1.7/Poor	1.9/Good	1.7/Fair	1.6/Good	0.5/Good	5.5	13.0	3.25	106	755	0.96	31.0
2780	5.36	4.33	1.1	1.7/Poor	1.6/Poor	1.6/Good	1.6/Good	0.75/Good	6.0	13.0	3.25	97	755	0.94	31.0
2820	5.36	4.33	1.1					1.6/Fair	6.0	13.0	3.25	97	755		11.4
2870	5.36	4.33	1.1	2.1/Poor	1.7/Poor	1.7/Good	1.6/Good	0.9/Good	6.0	13.0	3.25	97	755	1.0	31.0
2890	5.36	4.33	1.1	1.2/Good	1.8/Good	2.0/Fair	1.8/Good	1.3/Good	5.0	13.0	3.25	117	755	0.88	29.5
2930	5.36	4.41	1.1	0.75/Good	0.75/Good	0.9/Good	---	0.3/Good	10.0	13.0	3.25	59	755	0.76	31.0
2960	5.36	3.41	1.1	1.5/Good	1.8/Good	1.5/Good	1.3/Good	0.5/Fair	5.0	13.0	3.25	117	755	0.75	31.0
3080	5.36	5.13	1.1	---	0.95/Good	1.8/Fair	1.3/Poor	0.5/Good	5.0	13.0	3.25	117	755	0.62	21.0
3020	5.36	4.13	1.1	1.6/Fair	1.8/Fair	1.5/Fair	1.1/Good	0.75/Good	5.5	13.0	3.25	106	755	0.79	30.5
3070	5.36	5.13	1.1	1.1/Fair	1.1/Fair	1.1/Good	1.1/Fair	0.8/Good	5.5	13.0	3.5	104	755	0.61	31.0
3090	5.36	3.13	1.1	1.1/Poor	1.0/Poor	1.0/Good	0.95/Good	0.6/Good	5.5	13.0	3.5	104	755	0.55	31.0
3130	5.36	5.13	1.1	1.2/Poor	1.1/Good	1.3/Good	0.9/Good	0.75/Good	5.65	13.0	3.125	105	755	0.63	31.0

Table III

(continued)

Low Temperature Titanium Carbonitride Run Data

Run Number	Gas Flows: Inner Nozzle (ℓ/min)	Gas Flows: Outer Nozzle (ℓ/min)	Gas Flows: Chamber Gas[(e)] (ℓ/min)	Coating Thickness/Adhesion From Exhaust End: 1/2"	5"	11"	16"	21"	Pull Speed (in./hr)	Heat Zone Size (in.)	Nozzle Position Into Heat Zone (in.)	Reaction Time (min)	Average Reactor Temp. (°C)	Average Dep. Rate (mils/hr)	Final Nozzle Position (in.)
3150	5.36	4.33	1.1	0.75/good	0.75/good	0.8/good	0.5/good	0.4/good	14.9	13	3.25	39	755	108	31.0
3170[(f)]	5.36	4.33	1.1	/good	/good	/good	/good	/good	15.0	13	3.25	39	755	---	31.0
3220[(f)]	5.37	4.33	1.1	/good	/good	/good	/good	/good	15.0	13	3.25	39	755	---	31.5
3240[(g)]	8.70	0.99	1.1	1.2/good	0.6/good	1.4/poor	1.2/good	0.5/good	5.65	13	3.25	104	755	0.65	25.5
3280	2.73	4.33	1.1	0.65/good	0.8/good	0.75/good	0.6/good	0.4/good	15.0	13	3.25	39	755	1.00	31.0
3340	2.71	1.67	1.1	---	---	---	---	---	15.0	13	3.25	39	755	---	32.5
3350	2.71	2.01	1.1	0.5/good	0.5/good	0.5/good	0.3/good	0.15/good	15.0	13	3.25	39	755	0.69	31.0
3350	2.71	1.67	1.1	0.5/good	0.5/good	0.45/good	0.3/good	0.2/good	15.0	13	3.25	39	755	0.69	31.0
3380[(g)]	3.22	1.57	1.1	---	---	0.2/poor	---	---	15.0	13	3.25	39	755	---	31.2
3420[(g)]	3.73	4.14	1.1	0.3/good	0.3/good	0.3/poor	0.3/poor	0.15/poor	15.0	13	3.25	39	755	0.45	32.0
3440[(g)]	3.73	4.14	1.1	0.3/good	0.6/good	0.6/poor	0.5/poor	0.2/poor	7.5	13	3.25	78	755	0.45	31.0
3480	6.88	0.99	1.1	0.45/good	0.45/good				7.5	Varied	Varied		755		19
3510[(g)]	6.88	0.99	1.1	0.4/fair	0.6/good	0.8/poor	0.45/fair	0.2/poor	7.5	13	4.25	70	755	0.47	28
3560[(g)]	6.84	0.99	1.1	0.7/good	1.3/good	1.3/poor	1.3/poor	0.65/good	7.5	13	3.75	74	755	0.93	31
3650[(h)]	2.73	4.33	1.1		0.45/good/Z390				4.5	13	3.75	116	755		19
0051[(h)]	2.76	5.32	1.1		0.5/good				4.5	13	3.75	116	760		19
0071	2.73	4.33	1.1	1.3/poor	1.0/poor	1.9/good	2.8/good	0.9/good	4.0	13	3.25	146	755	0.74	23.5
0121	5.37	4.33	1.1	2.6/good	2.8/good	2.6/poor		0.5/good	4.0	13	3.25	146	755	1.02	23

(e) Gas in barrel ID on single nozzle runs
(f) 0.5 mil coated barrels shipped for test firing
(g) Single nozzle runs
(h) Deposit on 0.75" ID pipe

Table III
(continued)

Low Temperature Titanium Carbonitride Run Data

Run Number	Gas Flows: Inner Nozzle (ℓ/min)	Gas Flows: Outer Nozzle (ℓ/min)	Gas Flows: Chamber Gas (ℓ/min)	Coating Thickness/Adhesion From Exhaust End: 1/2"	5"	11"	16"	21"	Pull Speed (in./hr)	Heat Zone Size (in.)	Nozzle Position Into Heat Zone (in.)	Reaction Time (min)	Average Reactor Temp. (°C)	Average Dep. Rate (mils/hr)	Final Nozzle Position (in.)
0971	5.37	4.33	1.1	0.6/	0.7/	0.6/	0.4/	0.2/	5.0	13	3.25	117.0	755	0.29	32
0981	5.37	4.33	1.1	1.8/Good	1.9/Poor	1.6/Good	1.3/Good	0.7/Good	5.65	13	3.25	103.5	755	0.93	29
1031	5.37	4.33	1.1	2.2/Good	1.7/Good	1.8/Poor	2.0/Poor	0.9/Good	5.65	13	3.25	103.5	755	0.93	27
1051	5.37	4.33	1.1	1.5/Good	1.6/Good	1.7/Good	1.5/Poor	0.8/Good	5.65	13	3.63	95.0	755	0.92	25
1111	5.37	4.33	1.1	2.0/Good	1.8/Good	1.5/Good	1.3/Good	0.8/Good	7.07	13	3.63	79.5	770	1.14	27
1131	5.37	4.33	1.1	1.6/Good	1.5/Good	1.3/Good	1.2/Good	0.9/Good	7.07	13	4.0	76.4	755	1.06	26
1171	5.37	4.33	1.1	—	—	—	—	—	6.5	13	4.0	83.1	755	—	28
1191	5.37	4.33	1.1	—	—	—	—	—	7.07	13	4.0	76.4	755	—	28
1241	5.37	4.33	1.1	1.9/Good	1.6/Good	1.5/Good	1.3/Poor	1.0/Good	7.07	13	4.0	76.4	755	1.15	28
1301	5.37	4.33	1.1	1.3/Good	1.2/Good	1.1/Good	1.2/Good	1.2/Good	7.64	13	4.0	70.7	755	1.02	28
1321	5.37	4.33	1.1	1/3/Good	1.2/Good	1.1/Good	1.2/Good	1.0/Good	8.48	14	4.25	69.2	755	1.00	28
1331	5.37	4.33	1.1	—	—	—	—	—	8.34	14	4.25	70.2	755	—	28
1371 (i)	5.37	4.33	1.1	—	—	—	—	—	8.34	14	4.25	70.2	755	—	28
1381 (i)	5.37	4.33	1.1	—	—	—	—	—	7.3	14	4.25	80.2	755	—	28
1391 (i)	5.37	4.33	1.1	—	—	—	—	—	7.3	14	4.25	80.2	755	—	28
1401 (i)	5.37	4.33	1.1	—	—	—	—	—	8.34	14	4.25	70.2	755	—	28
1441	5.37	4.33	1.1	—	—	—	—	—	7.3	14	4.0	82.2	755	—	28
1451	5.37	4.3	1.1	0.9/Good	0.5/Good	0.9/Good	0.7/Good	0.6/Good	13.75	14	4.0	43.7	755	1.1	28
1471 (i)	5.37	4.3	1.1	—	—	—	—	—	13.75	14	4.0	43.7	755	—	28
1461 (i)	5.37	4.3	1.1	—	—	—	—	—	13.75	14	4.0	43.7	755	—	28
1531 (j)	5.37	4.3	1.1	1.6/Good	1.3/Good	—	—	—	6.25	14	4.0	96.1	755	0.91	10
1551 (j)	5.37	4.3	1.1	—	—	1.4/Good	1.2/Good	1.0/Good	8.1	14	4.0	74.1	755	0.97	28

(i) Barrels sent for test firing

(j) Coated over chromium plated barrel ID

Table IV

Statistical Plan, Low Temperature Titanium Carbonitride

			RUN PARAMETERS				COATING THICKNESS		
Treatment	Run Number	Series	H_2	Anion Gas	Metal Reactant	Temp	Base	Actual	Calculated
abd	1450B	1	1	1	-1	1	1 mil	1.2	1.355
d	1530	2	-1	-1	-1	1		1.0	0.805
cd	1400	3	-1	-1	1	1		1.1	1.275
bd		4	-1	1	-1	1			
abcd	1450	5	1	1	1	1		1.65	1.795
acd		6	1	--	1	1			
bcd	1460	7	-1	1	1	1		1.4	1.545
ad	1550	8	1	-1	-1	1		1.3	1.055
ab		9	1	1	-1	-1			
I	1460B	10	-1	-1	-1	-1		0.5	0.205
c	1530B	11	-1	-1	1	-1		0.35	0.645
ab	1480	12	1	1	-1	-1		0.75	0.725
abc	1550B	13	1	1	1	-1		0.65	1.195
ac	1410	14	1	-1	1	-1		0.75	0.895
bc		15	-1	1	1	-1			
a	1410B	16	1	-1	-1	-1		0.7	0.455

indicates that additional experimental values would be required for refinement to an exact mathematical description. The quality, rate, and control of the coating process indicated that sufficient data were available to provide barrels of acceptable quality to meet the program goals.

Figure 10 shows plots of the data taken to determine the influence of reaction parameters on coating thickness of low temperature titanium carbonitride from the statistical plan. The slopes of the lines in each plot indicate the relative magnitude of the influence of the reaction variable on the coating thickness. Hydrogen flow was a positive contributor in all cases, indicating increased hydrogen flow yielded a faster deposition rate. The anion concentration plot showed an interaction effect; in some reaction conditions it was a positive contributor, while in others it contributed negatively to the deposition rate. Likewise, the metal concentration was a non-monotonic effect which contributed positively in some cases, negatively in others. The final plot shows that temperature was a positive contributor for all reaction conditions tested. Some interaction effect was also indicated by the fact the curves in the temperature plot cross rather than having parallel slopes.

3. <u>High Temperature Process Parameter Optimization</u>

A similar statistical plan was outlined for the high temperature process. The runs are listed in Table V. The plan for this series differed from that for the low temperature series in that two sets of three-variable, two-level experiments were run in a one-half replicate magnitude. Six runs were made to permit a preliminary evaluation of the influence of all four reaction parameters. The interaction effects appeared to be highly significant, and full replication would have been required for a complete mathematical description. The influences of the reaction parameters are shown in the plots of Figures 11 and 12. As with the low temperature process, temperature seems to be the major influence on coating deposition rate. Other variables appeared to have less influence. Individual high temperature experiments were run in the order listed in Table VI.

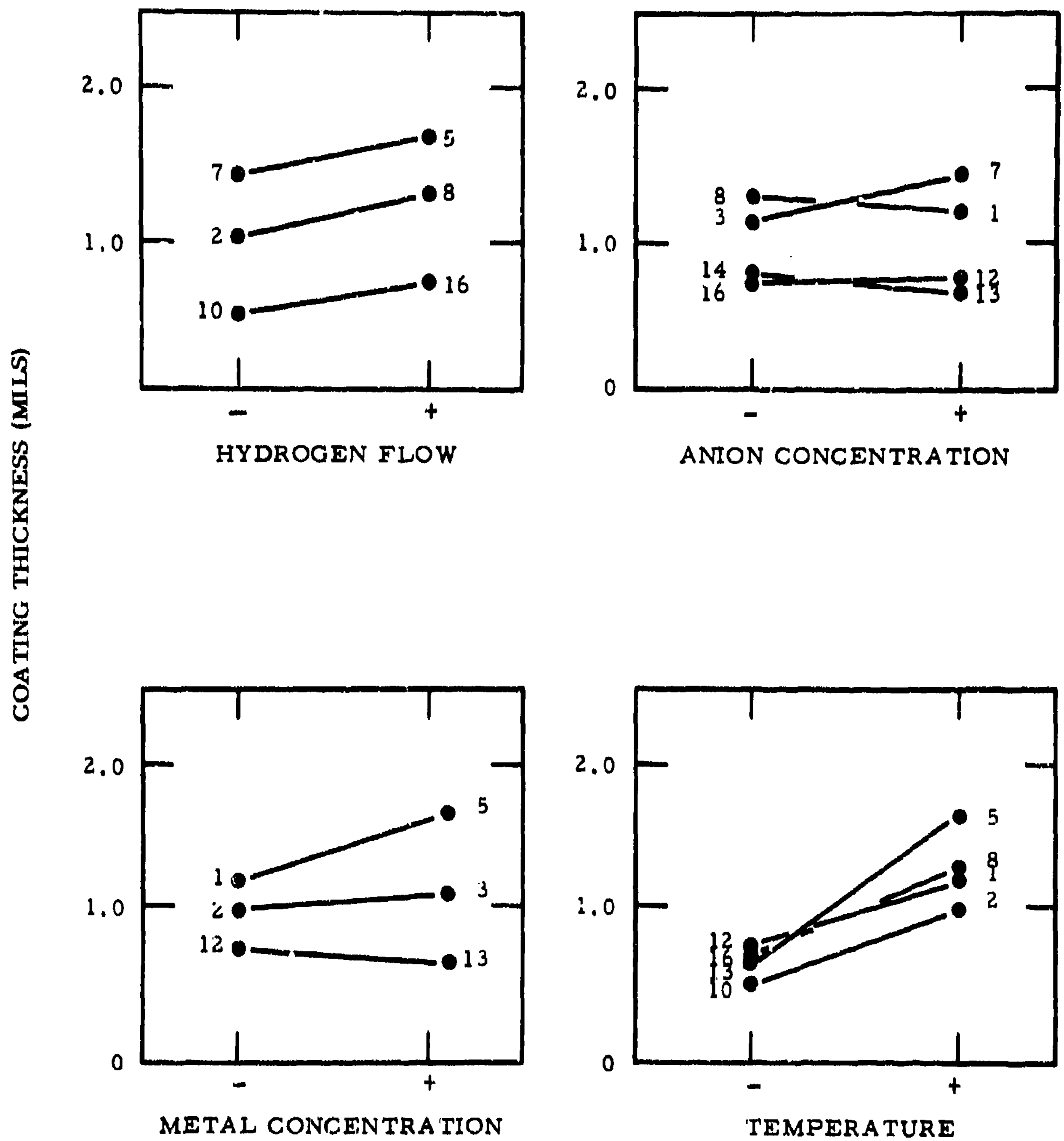


Figure 10 Influence of Reaction Parameters on Coating Thickness of Low Temperature Titanium Carbonitride

Table V

Statistical Plan, High Temperature Titanium Carbonitride

Treatment	Run Number	Series	RUN PARAMETERS				COATING THICKNESS			
							900°C		1000°C	
			Bypass H_2	Metal Conc.	Inert Gas	Anion Conc.	Base	Actual	Base	Actual
ad	1270140	1	+	-	-	+	0.45	0.45	1.5	1.3
bc	1270141	2	-	+	+	-		0.30		0.9
ab	1270142	3	+	+	-	-		0.25		1.0
I		4	-	-	-	-				
ac	1270147	5	+	-	+	-		0.15		0.6
cd		6	-	-	+	+				

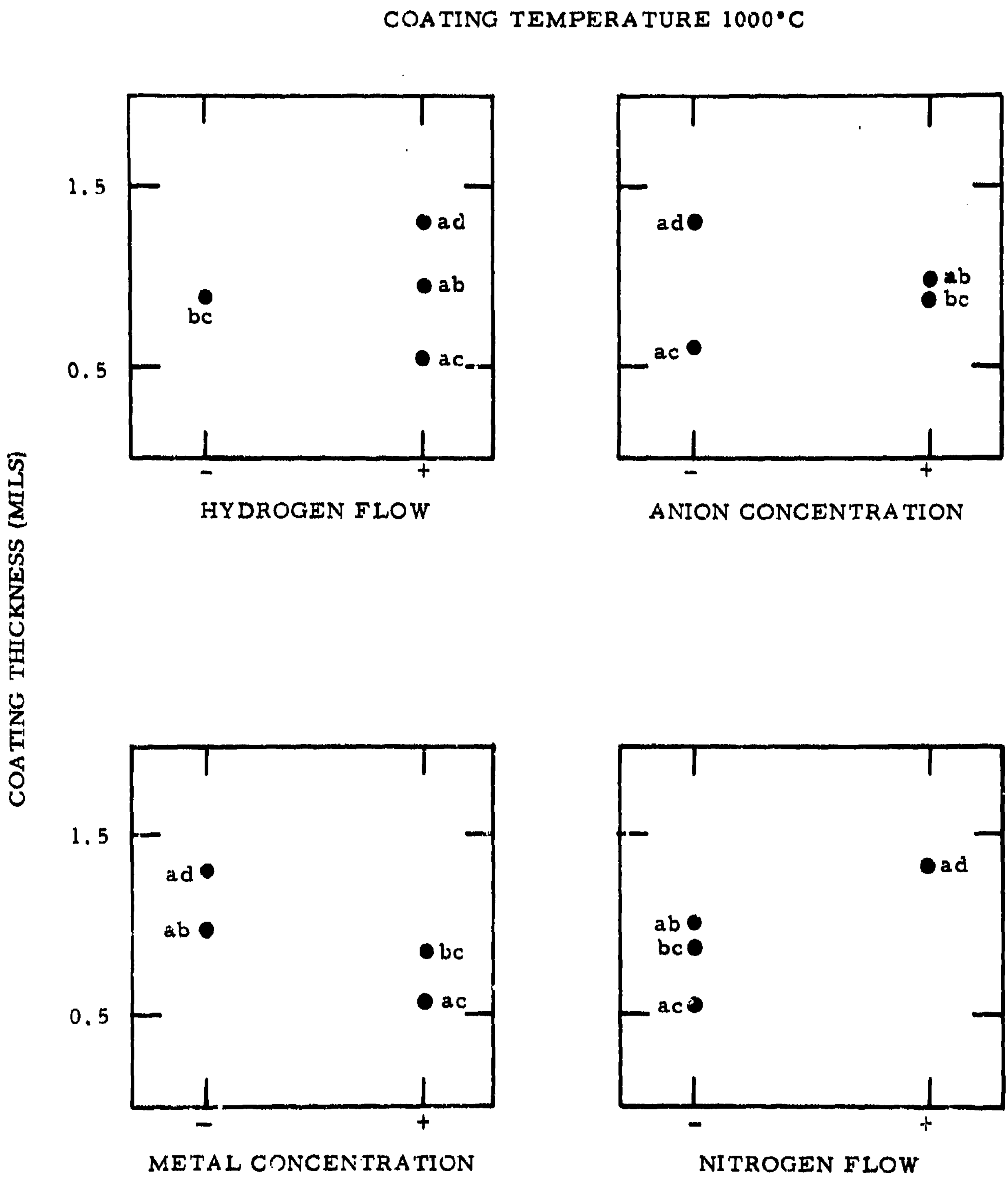


Figure 11 Influence of Reaction Parameters on Coating Thickness of High Temperature Titanium Carbonitride

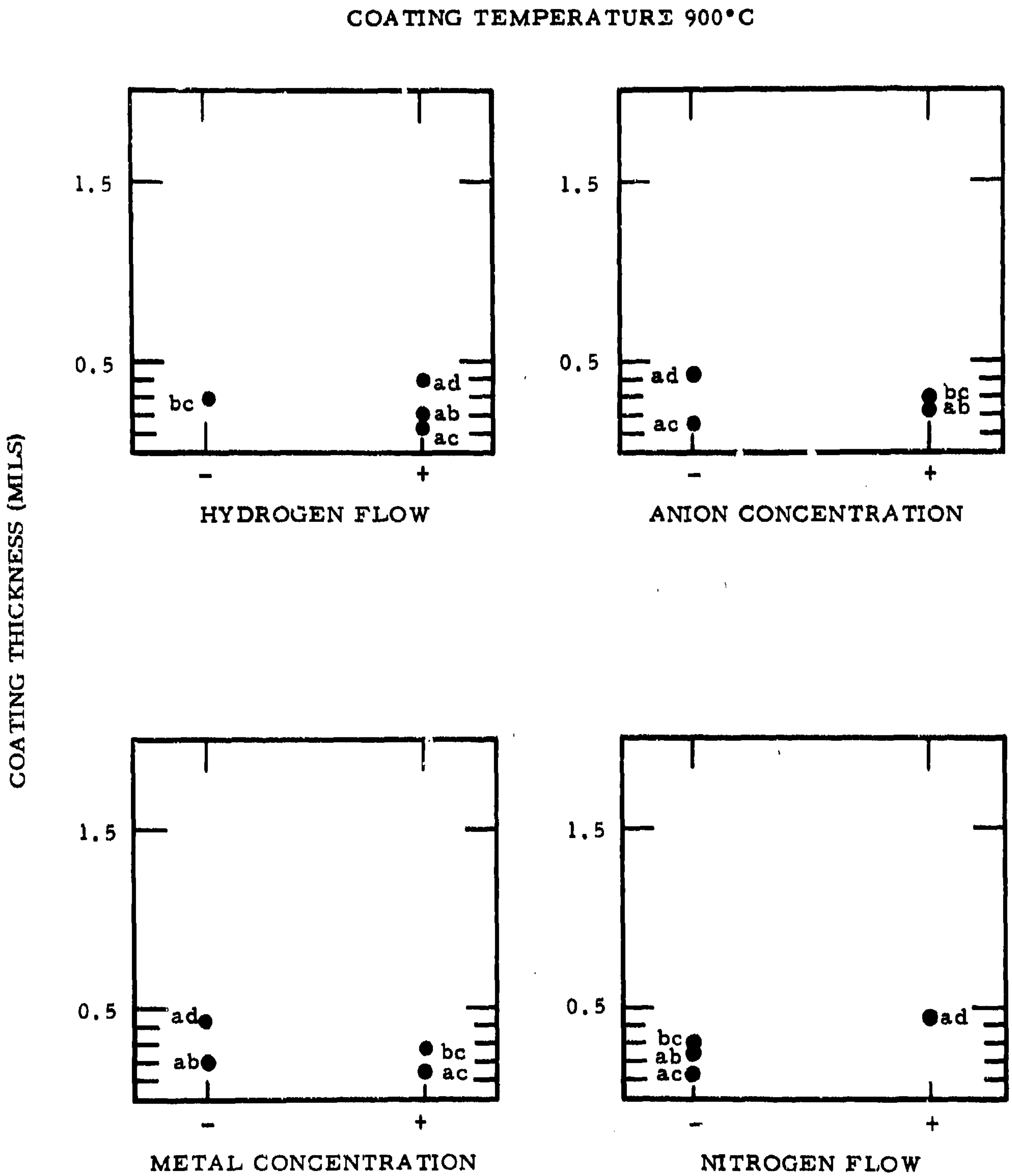


Figure 12 Influence of Reaction Parameters on Coating Thickness of High Temperature Titanium Carbonitride

Table VI

High Temperature Titanium Carbonitride Run Data

Run Number	Gas Flows: Total Reactant Gases (ℓ/min)	Gas Flows: Chamber Gas (ℓ/min)	Coating Thickness/Adhesion/Hardness* From Exhaust End: 1/2"	5"	11"	16"	21"	Pull Speed (in./hr)	Heat Zone Size (in.)	Nozzle Position Into Heat Zone (in.)	Reaction Time (min)	Average Furnace Temp. (°C)	Average† Dep. Rate (mils/hr)	Final‡ Nozzle Position (in.)
1270096	1.78	0.2	4.0/Bad/2400	3.5/Good/2200	1.8/Good/1900	0	0	15	12	3	24	1100	10	21.5
1270098	1.79	0.2	0.5/Fair	0.5/Good	0.5/Good	0	0	15	12	3	24	900	1.2	21.5
1270100	0.456	0.2	1.0/Fair	1.5/Good	1.3/Good	1.3/Good	0	15	12	3	24	900	2.4	21.5
1270103	1.010	0.2	1.0/Fair	1.0/Good	1.1/Good	0.8/Good	0	15	12	3	24	900	2.4	21.5
1270104	1.010	0.2	1.5/Fair	1.5/Good	1.3/Good	0.5/Good	0	15	12	3	24	1000	3.7	21.5
1270105	1.010	0.2	0	0.2/Bad	0	0	0	15	12	6.5	24	900	0	21.5
1270106	0	0.2	- (Test Run)	-	-	-	-	15	12	6.5	24	-	-	21.5
1270107	1.010	0.2	0.2/Poor	0.3/Fair	0.2/Fair	0.3/Fair	0	15	12	6.5	24	950	0.5	21.5
1270110	1.010	0.2	0.7/Fair	0.8/Good	0.8/Good	0.5/Good	0.05	15	12	6.5	24	1000	2.4	21.5
1270111	1.010	0.2	1.1/Bad	1.0/Fair	0.6/Fair	0.5/Fair	0.4/Fair	7.5	12	6.5	48	1000	1.3	21.5
1270113	1.010	0.2	1.3/Bad	1.3/Good	0	0	0	7.5	12	6.5	48	1000	1.6	21.5
1270114	1.010	0.2	1.9/Bad	1.9/Good	1.9/Good	1.8/Good	0.1/Fair	7.5	12	6.5	48	1000	2.4	21.5
1270117	1.400	0.2	1.0/Fair	1.2/Good	1.1/Good	0.8/Good	0	7.5	12	6.5	48	1000	1.14	21.5
1270118	1.400	0.2	0.1/Fair	0	0.05/Fair	0	0	7.5	12	6.5	48	900	0.12	21.5
1270120	1.010	0.2	1.4/Bad	0.9/Good	1.1/Good	1.1/Good	0.2/Good	7.5	12	6.5	48	1000	1.12	21.5
1270121	1.010	0.2	2.1/Poor	2.4/Good	2.3/Good	2.3/Good	0.4/Good	7.5	12	6.5	48	1000	2.40	21.5
1270125	1.010	0.2	2.2/Good	2.7/Good	2.4/Good	1.4/Good	0.8/Good	7.5	12	6.5	48	1000	2.40	21.5
1270126	1.010	0.2	2.5/Good/2790	2.3/Good/2600	2.1/Good/2600	2.1/Good/2600	1.1/Good/2500	7.5	12	6.5	48	1000	2.50	21.5
1270127	1.18	0.2	2.4/Good	1.5/Good	1.5/Good	1.2/Good	0.3/Good	7.5	12	6.5	48	1000	1.80	21.5
1270131	1.18	0.2	0.2/Good	0.2/Good	0.3/Good	0.5/Good	0.2/Good	7.5	12	6.5	48	900	0.38	21.5
1270132	1.18	0.2	1.4/Good/2600	1.5/Good/3000	1.5/Good/2700	1.5/Good/2700	1.0/Good/2200	11.3	12	6.5	32	1000	2.60	21.5
1270135	1.18	0.2	1.4/Good/3100	1.2/Good/2600	1.2/Good/2643	1.1/Good/3200	1.0/Good/3100	11.3	12	6.5	32	1000	2.00	21.5

* mils/ /KHN25
† Based on areas getting complete deposition time
‡ From exhaust end

Table VI

(continued)

High Temperature Titanium Carbonitride Run Data

Run Number	Gas Flows: Total Reactant Gases (l/min)	Gas Flows: Chamber Gas (l/min)	Coating Thickness/Adhesion/Hardness Measured From Exhaust End: 1/2"	5"	11"	16"	21"	Pull Speed (in./hr)	Heat Zone Size (in.)	Nozzle Position Into Heat Zone (in.)	Reaction Time (min)	Average Furnace Temp. (°C)	Average Dep. Rate (mils/hr)	Final Nozzle Position (in.)
1270138	1.2	0.2	0.55/Good	0.4/Good	0.2/Good	0.45/Good	0.45/Good	7.5	12	6.5	32	1000	0.77	21.5
1270140	1.97	0.2	0.4/Poor	Undetermined				11.3	12	6.5	32	1000	0.364	21.5
1270140	1.97	0.2			0.45/Poor	0.45/Poor		11.3	12	6.5	32	900	0.84	21.5
1270141	1.61	0.2	0.8/Fair	0.9/Fair				11.3	12	6.5	32	1000	1.6	21.5
1270141	1.61	0.2			0.3/Fair	0.3/Fair	/Poor	11.3	12	6.5	32	900	0.56	21.5
1270142	2.21	0.2	0.9/Fair	1.0/Fair				11.3	12	6.5	32	1000	1.78	21.5
1270142	2.21	0.2			0.45/Fair	0.25/Fair		11.3	12	6.5	32	900	0.66	21.5
1270146	3.91	0.2	0.55/Poor	?/Poor				11.3	12	6.5	32	1000	1.03	21.5
1270146	0.91	0.2			0.6/Poor	0.5/Poor		11.3	12	6.5	32	900	1.03	21.5
1270147	2.31	0.2	0.7/Fair	0.6/Fair				11.3	12	6.5	32	1000	1.22	21.5
1270147	2.31	0.2			0.35/Fair	0.15/Fair		11.3	12	6.5	32	900	0.37	21.5
1270152	1.80	0.2	1.0/Fair	1.1/Fair				11.3	12	6.5	32	1000	1.90	21.5
1270152	1.8	0.2			0.45/Fair	0.45/Fair	0.1/Fair	11.3	12	6.5	32	900	0.84	21.5
1270156	New Heater Temperature Profile Check							11.3	12	6.5	—	100	--	21.5
1270170		0.2	0.9/Good	0.8/Good				11.3	12	6.5	32	1000	1.6	21.25
1270170	1.18	0.2			0.2/Good			11.3	12	6.5	32	900	0.38	21.25
1270174**	1.18	0.2	1.2/Good	1.1/Good	1.0/Good			11.3	12	7.5	32	1000	2.0	21.25
1270175**	1.18	0.2	Plugged System					—	12	7.5	--	1000	--	21.25
1270176**	1.18	0.2	0.6/Good	0.5/Good	0.5/Good	0.4/Good		11.3	12	7.5	32	1000	0.94	21.25
1270180	1.18	0.2	0.8/Good	0.4/Good	0.3/Good	0.3/Good		11.3	12	7.5	32	1000	--	221.25
1270181	1.18	0.2	Plugged System					11.3	12	7.5	32	1000	--	21.25

** Two Stage Heater

Table VI
(continued)

High Temperature Titanium Carbonitride Run Data

Run Number	Gas Flows: Total Reactant Gases (ℓ/min)	Gas Flows: Chamber Gas (ℓ/min)	Coating Thickness/Adhesion/Hardness Measured From Exhaust End: 1/2"	5"	11"	16"	21"	Pull Speed (in./hr)	Heat Zone Size (in.)	Nozzle Position Into Heat Zone (in.)	Reaction Time (min)	Average Furnace Temp. (°C)	Average Dep. Rate (mils/hr)	Final Nozzle Position (in.)
1270182	1.18	0.2	0.5/Good	0.8/Good	0.5/Good	System Plugged		11.3	12	7.5	32	1000	1.3	21.25
1270188	1.18	0.2	1.2/Good	1.2/Good	1.3/Good	1.3/Good	0.3/Good	11.3	12	6.5	32	1000	2.3	21.25
1270189	1.18	0.2	2.0/Good	2.4/Good	1.2/Good	1.8/Good	1.1/Good	11.3	12	6.5	32	1027	3.4	21.25**
1270191	1.18	0.2	1.3/Good	1.1/Good	1.0/Good	1.0/Good	None	11.3	12	7.5	32	1000	2.0	21.25**
1270195	1.18	0.2	1.1/Good	1.35/Good	1.15/Good	1.25/Good	0.1/Good	7.5	12	7.5	48	1000	1.5	21.25**
1270196	1.18	0.2	2.0/Good	2.6/Good	2.0/Good	1.80/Good	None	7.5	12	7.5	48	1010	2.6	21.25**
1270202	1.18	0.2	1.3/Good	System Clogged				11.3	12	6.5	32	1000	--	21.5
1270203	1.18	0.2	1.7/Good	1.8/Good	1.6/Good	1.6/Good	0.2/Good	11.3	12	6.5	32	1000	3.2	21.5
1270204	1.18	0.2	1.2/Good	1.2/Good	1.5/Good	1.7/Good	0.6/Good	11.3	12	6.5	32	1000	2.6	21.5
1270205	1.18	0.2	1.45/Good	0.8/Good	0.8/Good	0.7/Good	0.4/Good	11.3	12	6.5	32	1000	0.94	21.5
1270209	1.18	0.2	1.35/Good	2.3/Good	1.9/Good	1.8/Good	0.7/Good	11.3	12	6.5	32	1010	3.9	21.5
1270210	1.18	0.2	2.9/Bad	1.8/Good	1.4/Good	1.3/Good	0.5/Good	11.3	12	6.5	32	1020	3.5	21.5
1270212	1.18	0.2	0.8/Good	1.45/Good	1.55/Good	1.3/Good	0.5/Good	11.3	12	6.5	32	1000	2.4	21.5
1270217	1.18	0.2	1.7/Good	1.1/Good	1.1/Good	0.65/Good	0.1/Good	11.3	12	6.5	32	1000	[illegible]	21.5
1270218	1.18	0.2	1.45/Good	1.1/Good	0.6/Good	0.6/Good	0.2/Good	11.3	12	6.5	32	1000	1.7	21.5
1270219	1.18	0.2	1.35/Good	1.4/Good	1.2/Good	1.1/Good	0.1/Good	11.3	12	6.5	32	1000	2.3	21.5
1270223	1.18	0.2	1.6/Good	1.2/Good	0.7/Good	0.7/Good	None	11.3	12	6.5	32	1000	1.9	21.5
1270224	1.18	0.2	1.6/Good	1.4/Good	1.1/Good	1.0/Good	0.1/Good	11.3	12	6.5	32	1000	2.2	21.5
1270225	1.18	0.2	1.5/Good	1.0/Good	0.8/Good	0.7/Good	0.2/Good	11.3	12	6.5	32	1000	1.9	21.5
1270226	1.18	0.2	1.4/Good	1.1/Good	0.9/Good	0.8/Good	0.6/Good	7.5	12	6.5	38.5	1000	1.9	22.0

* Two Stage Heater

** Scrap Gun Barrels

Table VI

(continued)

High Temperature Titanium Carbonitride Run Data

Run Number	Gas Flows		Coating Thickness/Adhesion Measured From Exhaust End					Pull Speed (in./hr)	Heat Zone Size (in.)	Nozzle Position Into Heat Zone (in.)	Reaction Time (min)	Average Reactor Temp (°C)	Average Dep. Rate (mils/hr)	Final Nozzle Position (in.)
	Total Reactant Gases (ℓ/min)	Chamber Gas (ℓ/min)	1/2"	5"	11"	16"	21"							
1270229	1.18	0.2	2.0/good	1.25/good	0.85/good	1.0/good	0.45/good	9.4	12	6.5	40	1000	1.9	22.0
1270231	1.18	0.2	1.9/good	1.7/good	1.5/good	1.0/good	0.35/good	11.3	12	6.5	32	1000	2.8	22.0
1270232	1.18	0.2	2.0/good	1.1/good	1.0/good	0.6/good	0.4/good	11.3	12	6.5	32	1000	2.2	21.5
1270236	1.20	0.2	0.4/good	0.3/good	0.3/good	0.3/good	0	11.3	12	6.5	32	1000	0.62	21.5
1270237	1.20	0.2	1.0/good	1.0/good	1.4/good	1.4/good	0.6/good	7.5	12	6.5	48	950	1.5	21.5
1270238	1.20	0.2	2.0/bad	1.7/good	1.0/good	1.0/good	0.6/good	11.3	12	6.5	32	1000	2.6	21.5
1270239	1.20	0.2	2.3/good	2.3/good	2.0/good	1.8/good	0.6/good	7.5	12	6.5	48	1000	2.6	21.5
1270240	1.18	0.2	0.8/good	1.2/good	1.2/good	1.3/good	0.6/good	11.3	12	6.5	32	1000	2.3	21.5
1270244	1.20	0.2	1.8/poor	2.0/poor	2.5/good	1.5/good	1.0/good	11.3	12	6.5	32	1025	3.6	21.5
1270246	1.18	0.2	1.0/good	1.0/good	1.0/good	1.0/good	0.8/good	7.5	12	8.5	48	1000	1.25	22.0
1270247	1.18	0.2	1.1/good	2.0/poor	2.2/good	2.0/good	1.0/good	7.5	12	8.5	48	1000	2.3	22.0

Table VI

(continued)

High Temperature Titanium Carbonitride Run Data

Run Number	Gas Flows: Total Reactant Gases (ℓ/min)	Gas Flows: Chamber Gas (ℓ/min)	Coating Thickness/Adhesion From Nozzle End: 1/2"	5"	11"	16"	21"	Pull Speed (in./hr)	Heat Zone Size (in.)	Nozzle Position Into Heat Zone (in.)	Reaction Time (min)	Average Furnace Temp. (°C)	Average Dep. Rate (mils/hr)	Final Nozzle Position (in.)
1270259	1.26	0.2	1.2/Good	1.5/Good	1.3/Good	1.2/Good	0.8/Good	7.5	12	6.2	48	1000	1.65	22
1270260	1.26	0.2	1.0/Good	1.15/Good	1.1/Good	1.0/Good	0.35/Good	7.5	12	6.2	48	1000	1.35	22
1270261	1.26	0.2	Test Barrel					7.5	12	6.2	48	1000		22
1270264	1.26	0.2	Test Barrel					7.5	12	6.2	48	1000		22
1270265	1.26	0.2	1.5/Good	1.4/Good	1.3/Good	1.1/Good	0.5/Good	7.5	12	6.2	48	1000	1.70	22
1270266	1.26	0.2	1.6/Good	1.7/Good	1.7/Good	1.2/Good	0.6/Good	5.6	12	6.2	65	1000	1.37	22
1270267	1.26	0.2	Test Barrel					4.3	12	6.2	84	1000		22
1270268	1.26	0.2	Test Barrel					4.3	12	6.2	84	1000		22
1270271	1.26	0.2	2.0/Good	2.2/Good	1.8/Good	1.7/Good	0.8/Good	7.5	12	6.2	48	1000	2.40	22
1270273	1.26	0.2	1.1/Good	1.35/Good	1.25/Good	1.25/Good	0.5/Good	7.5	12	5.2	48	1000	1.60	22
1270274	1.26	0.2	0.65/Good	0.89/Good	0.75/Good	0.9/Good	0.35/Good	7.5	12	5.2	48	950	1.03	22
1270275	1.26	0.2	0.9/Good	0.8/Good	0.6/Good	0.6/Good	0.4/Good	11.3	12	6.2	32	1000	1.30	22
1270278	1.18	0.2	0.8/Good	0.7/Good	0.7/Good	0.6/Good	0.3/Good	11.3	12	6.2	32	1000	1.30	22
1270279	1.18	0.2	1.0/Good	1.4/Good	1.3/Good	1.2/Good	0.3/Good	7.5	12	6.2	48	1000	1.55	22
1270281	1.18	0.2	Failure Due to Plugged Lines											
1270282	1.18	0.2	Test Barrel					7.5	12	6.2	48	1000		22
1270285	1.26	0.2	1.6/Good	1.6/Good	1.25/Good	1.25/Good	0.35/Good	7.5	12	6.2	48	1000	1.83	22
1270286	1.22	0.2	1.8/Good	1.3/Good	0.9/Good	0.75/Good	0.35/Good	7.5	12	6.2	48	1000	1.50	22

Table VI

(continued)

High Temperature Titanium Carbonitride Run Data

Run Number	Gas Flows: Total Reactant Gases (ℓ/min)	Gas Flows: Chamber Gas (ℓ/min)	Coating Thickness/Adhesion/Hardness Measured From Exhaust End: 1/2"	5"	11"	16"	21"	Pull Speed (in./hr)	Heat Zone Size (in.)	Nozzle Position Into Heat Zone (in.)	Reaction Time (min)	Average Furnace Temp. (°C)	Average Dep. Rate (mils/hr)	Final Nozzle Position (in.)
1270287	1.22	0.2	1.5/Good	1.25/Good	1.15/Good	0.9/Good	0.45/Good	7.5	12	6.2	48	1000	1.50	22
1270288	1.22	0.2	2.0/Good	2.0/Fair	1.5/Fair	1.3/Good	0.7/Good	7.5	12	6.2	48	1020	2.12	22
1270293	1.22	0.2	1.7/Good	2.2/Good	1.1/Good	1.1/Good	0.4/Good	7.5	12	6.2	48	1000	1.87	22
1270295	1.22	0.2	1.3/Good	1.2/Good	1.0/Good	0.3/Good	---	7.5	12	6.2	48	1009	1.20	22
1270296	1.22	0.2	1.75/Good	1.45/Good	1.5/Good	1.5/Good	0.7/Good	7.5	12	6.2	48	1000	1.95	22
1270300	1.31	0.2	1.5/Good	2.0/Good	1.0/Good	1.0/Good	0.5/Good	7.5	12	6.2	48	1010	1.75	22
1270301	1.31	0.2	0.5/Good	0.7/Good	0.5/Good	0.35/Good	0.15/Good	11.3	12	6.2	32	1010	1.00	22
1270302	1.31	0.2	1.0/Good	1.6/Good	1.4/Good	1.3/Good	0.6/Good	5.6	12	6.2	65	1010	1.20	22
1270306	1.31	0.2	1.1/Good	1.5/Good	1.0/Good	0.8/Good	0.4/Good	7.5	12	6.2	48	1010	1.38	22
1270309	1.31	0.2	0.7/Good	1.0/Good	0.9/Good	1.0/Good	0.6/Good	7.5	12	6.2	48	1010	1.12	22
1270310	0.91	0.2	0.6/Good	0.6/Good				11.3	12	6.2	32	1000	1.13	22
1270310	0.91	0.2			0.3/Good	0.3/Good	0.1/Good	11.3	12	6.2	32	900	0.56	22
1270313	1.37	0.2	0.6/Good	0.75/Good				11.3	12	6.2	32	1000	1.30	22
1270313	1.37	0.2			0.35/Good	0.3/Good	NONE	11.3	12	6.2	32	900	0.60	22
1270314	0.91	0.2	0.5/Good	0.7/Good	0.5/Good	0.4/Good	0.25/Good	11.3	12	6.2	32	1010	0.95	22
1270316	0.91	0.2	0.5/Good	0.65/Good	0.5/Good	0.5/Good	0.3/Good	11.3	12	6.2	32	1010	1.02	22
1270320	0.91	0.2	Good Barrel (Thin)					11.3	12	6.2	32	1010	---	22
1270321	0.91	0.2	0.5/Good	0.6/Good	0.5/Good	0.5/Good	0.4/Good	11.3	12	6.2	32	1000	1.02	22
1270322	0.91	0.2	Good Barrel (Thin)					11.3	12	6.2	32	1000	---	22

Table VI

(continued)

High Temperature Titanium Carbonitride Run Data

Run Number	Gas Flows: Total Reactant Gases (ℓ/min)	Gas Flows: Chamber Gas (ℓ/min)	Coating Thickness/Adhesion From Exhaust End: 1/2"	5"	11"	16"	21"	Pull Speed (in./hr)	Heat Zone Size (in.)	Nozzle Position Into Heat Zone (in.)	Reaction Time (min)	Average Furnace Temp. (°C)	Average Dep. Rate (mils/hr)	Final Nozzle Position (in.)
1270324	0.96	0.2	1.8/good	1.5/good	1.1/good	1.2/good	0.7/good	7.5	12	6.2	48	1000	1.75	22
1270327	1.18	0.2	0.35/good	0.4/good	0.4/good	0.4/good	0.35/good	11.3	12	6.2	32	1000	0.75	22
1270341	0.96	0.2	None	0.6/good	1.1/good	1.0/good	0.7/good	11.3	12	4.2	32	1000	0.95	22
1270343	1.18	0.2	None	0.8/good	1.2/good	1.2/good	0.8/good	11.3	12	4.2	32	1000	1.5	22

C. Process Control

1. Thickness Control and Taper

Coating thickness control and desired tapering of the coating were obtained. Since coating rate was constant for constant reaction conditions, taper was obtained by varying the relative rate of travel of the reaction zone by the barrel.

The series of micrographs in Figures 13 and 14 show typical coatings prepared by both processes in different thicknesses. The photomicrographs are taken on the corner of one rifling to illustrate the adhesion and the appearance of the coating on this extremely critical portion of the barrel. It is evident from the pictures that little spalling occurred during these experimental runs. The ability to deposit closely controlled thicknesses of coating is illustrated in these photomicrographs. The coatings shown in the photomicrographs are representative of "3/4 mil," "1 mil," and "2 mil" thicknesses on barrels sent for test firing. The tapered thinning toward the chamber, as shown in Figures 15 and 16, was achieved for all thicknesses in both the high and low temperature processes and was designed to give the bullet optimum velocity and accuracy. The diminishing diameter as the bullet proceeds down the barrel serves to hold the combustion gases behind it and give maximum "bite" into the lands.

Tables III and VI give run data for the program for both the high and low temperature processes. The run numbers correlate with the run numbers shown in the figures.

To examine possible changes in coating characteristics due primarily to convection current effects, the deposition direction in the high temperature vertical system was reversed from a bottom-to-top gas flow direction to a top-to-bottom direction in runs 1270341 and 1270343. Run conditions are given in Table VI. In the coating from No. 1270343, hardness variations from KHN_{25} 2105 near the substrate to 2313 in the center and to 2837 near the surface of the coating were observed. The deposition rate from this arrangement was double that of the standard process. An adverse effect on taper control

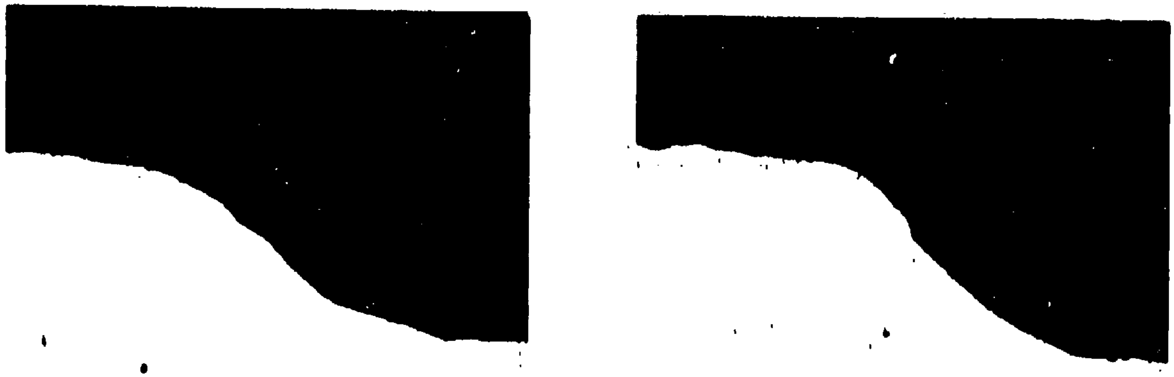


Figure 13 Photomicrographs of the Corner of Rifling of a Coated 7.62 mm Gun Barrel. Run No. 1900, ~ 1 mil thickness, low temperature process, 250X

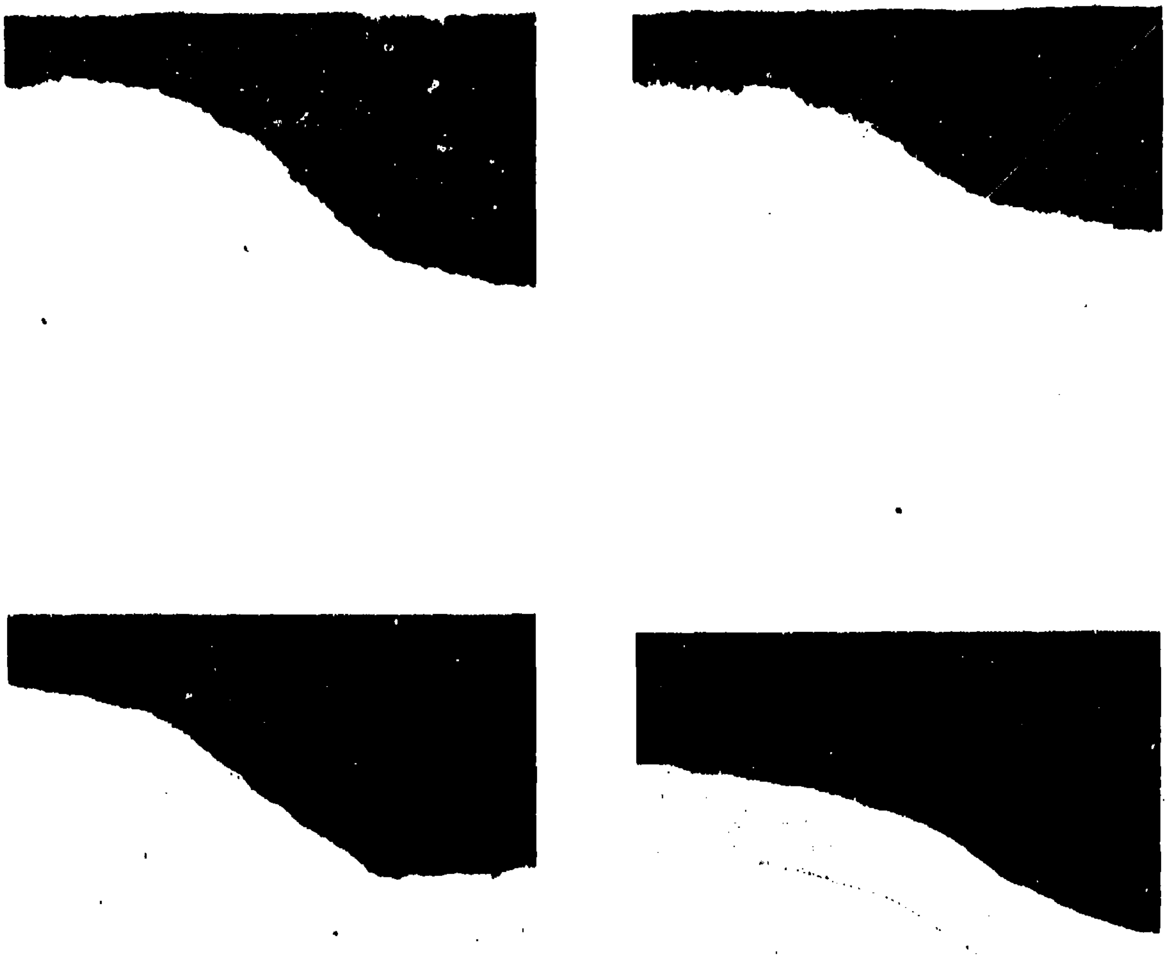


Figure 13 (Continued) Photomicrographs of the Corner of a Rifling of a Coated 7.62 mm Gun Barrel. Run No. 2080, ~ 2 mil thickness, low temperature process, 250X

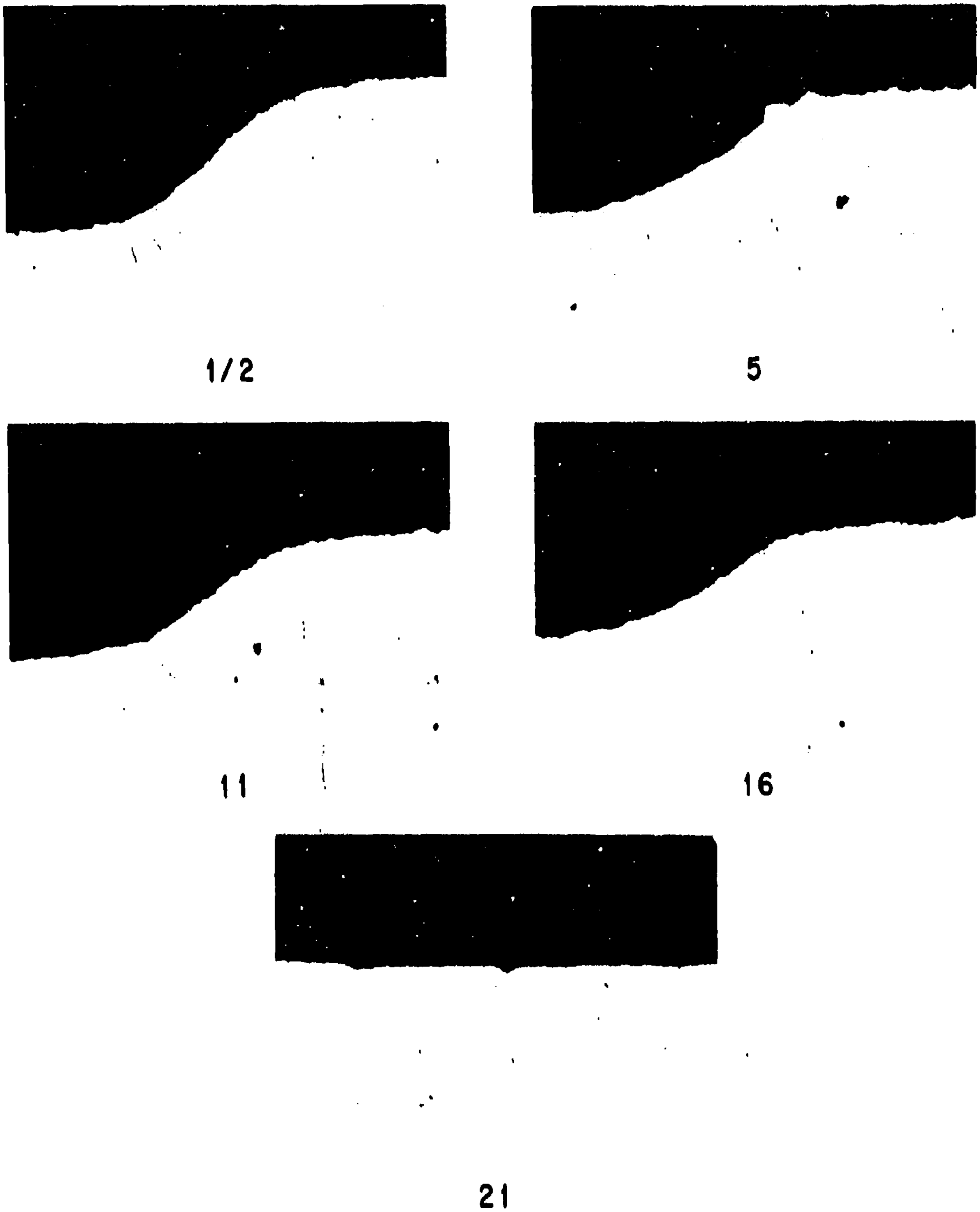
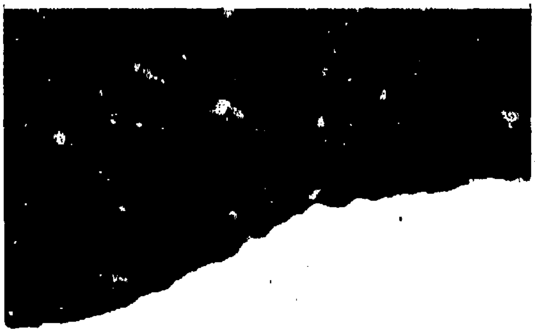


Figure 14 Photomicrographs of the Corner of Rifling of a Coated 7.62 mm Gun Barrel. Run No. 1270260, ~1 mil thickness, high temperature process (250X)

1/2

5

11



16

21

Figure 14 (Continued) Photomicrographs of the Corner of Rifling of a Coated 7.62 mm Gun Barrel. Run No. 1270266, ~ 2 mil thickness, high temperature process (250X)

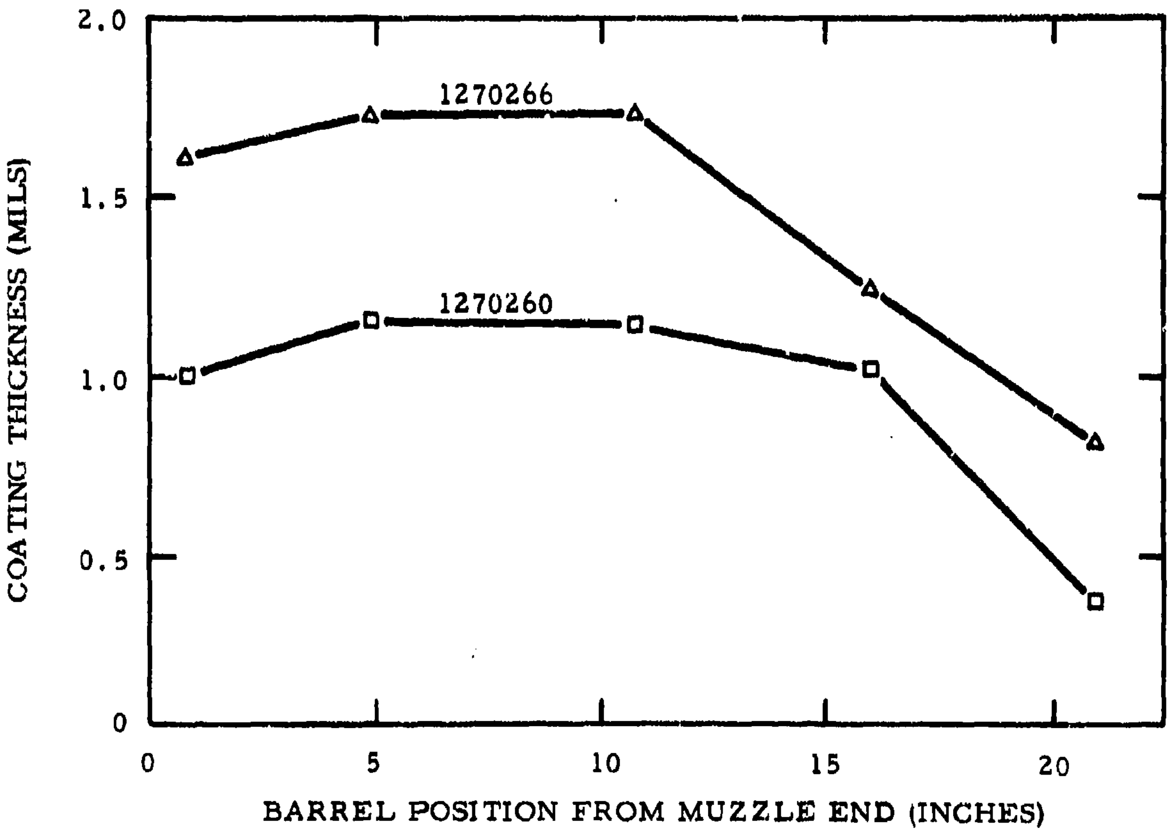


Figure 15 High Temperature Titanium Carbonitride Coating Thickness Profiles

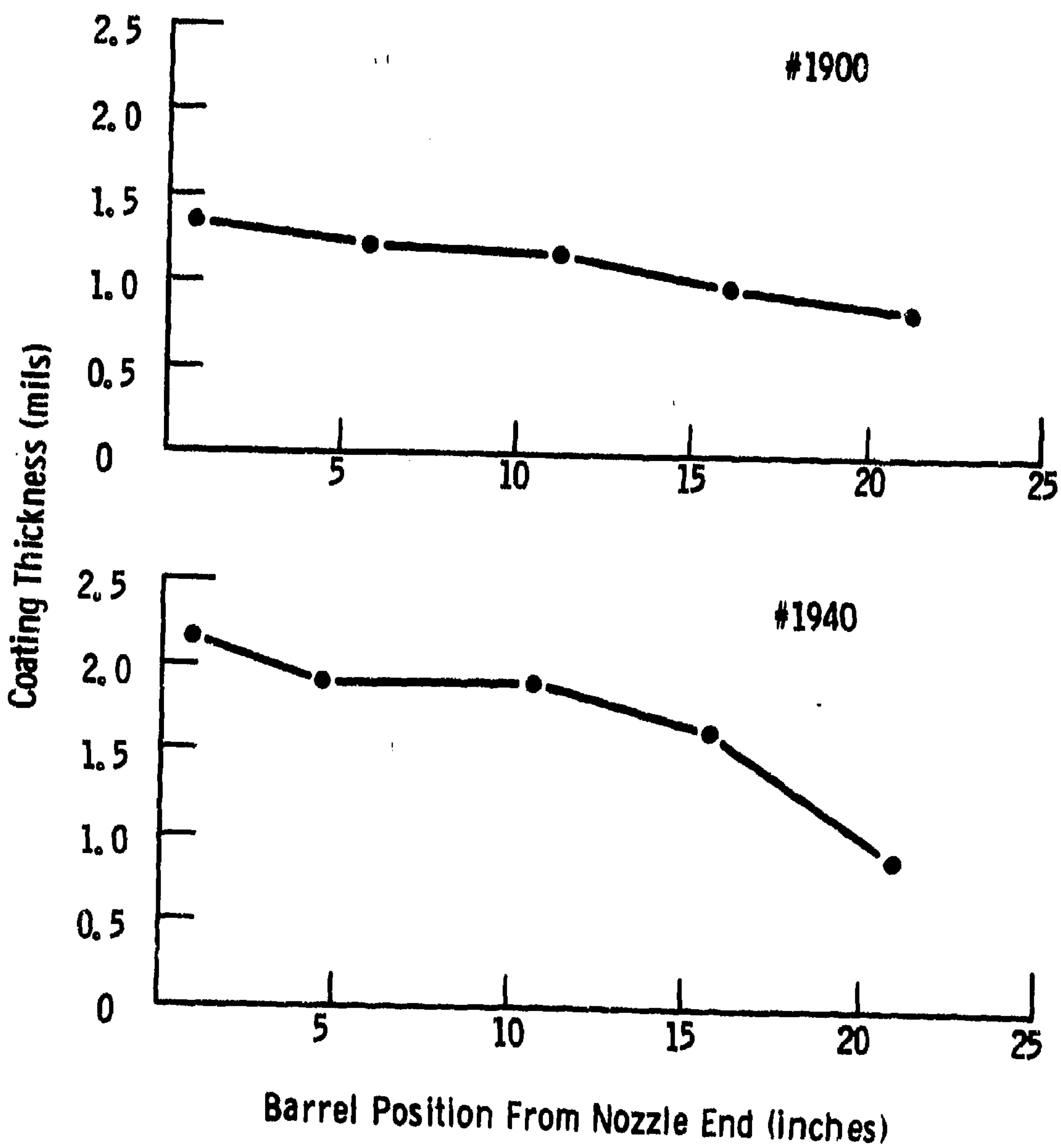


Figure 16 Coating Thickness Profile from Low Temperature Process

was noted. The coating had acceptable thickness variations from 11 inches into the barrel to the chamber end of the barrel; toward the muzzle end, however, the coating thickness tapered to zero rather than increasing to 1.4 mils. Extensive reactor design changes would have been required to compensate for the change in direction of the gas flow.

A set of coated barrels was prepared for firing tests using good barrels from which the chromium was electrostripped. The final diameter of these barrels was too large to justify test firing due to stripping of steel with the chromium. Examination of these barrels provided an opportunity to critically determine the thickness control in "product" barrels. The coating thickness was obtained from microscope measurement of cross sections of the barrels. Data from those measurements are shown in Table VII, where the coating OD is the steel ID, and the bore coating ID is the actual barrel ID. These measurements are expected to be accurate within 0.2 mil. The coating thickness was calculated as one-half of the difference between the barrel and steel diameters. The data taken by an air gage at Eglin Air Force Base is given for comparison in Table VIII. Agreement between the methods is poor, partly because much of the data was outside the calibration range of the air gage.

Plots of the coating thickness profile are given in Figure 17. The data in these plots show that the process gives close agreement between the land and groove coating thickness and demonstrates the ability to control coating thickness to varied levels and to taper coating along the barrel. Some preference in profile control is indicated for the low temperature process. Plots of the measured diameters are given in Figures 18(a) to 18(g).

2. Post-Treatment Effects

Hardness readings taken on low temperature coated barrel substrate material showed an average hardness of R_A57-58, much softer than the R_C30-35 found in the as-received substrate material shown in Figure 19. The coating temperature falls within an isothermal anneal range for the metal, which would account for the annealed condition and coarse-grained ferritic structure seen in the as-coated gun barrel material shown in Figure 20. Several

TABLE VII

Diameter of Barrels Measured with a Microscope

BARREL NUMBER	INCHES FROM MUZZLE	LAND-TO-LAND DIMENSIONS			GROOVE-TO-GROOVE DIMENSIONS		
		BORE COATING O.D.	BORE COATING I.D.	AVERAGE COATING THICKNESS	BORE COATING O.D.	BORE COATING I.D.	AVERAGE COATING THICKNESS
1006	0.5	.3050	.3010	.0020	.3128	.3088	.0020
1006	5.0	.3050	.3010	.0020	.3128	.3088	.0020
1006	11.0	.3057	.3022	.0018	.3130	.3096	.0017
1006	16.0	.3065	.3036	.0015	.3140	.3111	.0015
1007	0.5	.3048	.3022	.0013	.3121	.3099	.0011
1007	5.0	.3054	.3030	.0012	.3124	.3100	.0012
1007	11.0	.3057	.3033	.0012	.3125	.3103	.0011
1007	16.0	.3061	.3042	.0010	.3134	.3117	.0009
1010	0.5	.3056	.3044	.0006	.3131	.3117	.0007
1010	5.0	.3059	.3046	.0007	.3135	.3123	.0006
1010	11.0	.3066	.3055	.0006	.3142	.3131	.0006
1010	16.0	.3070	.3061	.0005	.3146	.3136	.0005
5001	0.5	.3054	.3035	.0010	.3128	.3110	.0009
5001	5.0	.3066	.3038	.0014	.3139	.3110	.0015
5001	11.0	.3077	.3050	.0014	.3150	.3125	.0013
5001	16.0	.3077	.3053	.0012	.3152	.3130	.0011
5004	0.5	.3051*	.3048*	-	.3121	.3096	-
5004	5.0	.3054	.3004	.0025	.3131	.3083	.0024
5004	11.0	.3066	.3021	.0022	.3140	.3098	.0021
5004	16.0	.3071	.3033	.0019	.3148	.3110	.0019
5015	0.5	.3045	.3036	.0005	.3121	.3111	.0005
5015	5.0	.3052	.3038	.0007	.3130	.3115	.0008
5015	11.0	.3058	.3049	.0005	.3135	.3127	.0004
5015	16.0	.3071	.3063	.0004	.3142	.3134	.0004

* Most of coating chipped off.

Table VIII

Barrel Diameters Measured by an Air Gage

Barrel I.D.	Type	Distance in inches from the breech end of the barrel: [illegible] Groove	Land	3" G	3" L	[illegible] G	L	[illegible] G	L	6" G	6" L	7" G	7" L	8" G	8" L	9" G	9" L	10" G	10" L	11"			
"A"	Std.	[illegible]	N/A	.3087	N/A	.3090	.3011	.3091	.3003	.3088	.3011	.3081	.3015	.3080	.3011	.3085	[illegible]	.3089	.3005	.3084	[illegible]	[illegible]	[illegible]
"B"	Std.	[illegible]	N/A	.3088	N/A	.3090	.3015	.3092	.3017	.3092	.3015	.3088	.3012	.3088	.3012	.3088	.3012	.3088	.3012	[illegible]	.3010	.3065	N/A
"C"	Std.	.3093	N/A	.3090	N/A	.3088	.3011	.3088	.3013	.3086	.3011	.3085	.3010	.3083	.3008	.3082	.3007	.3081	.3008	.3081	.3007	.3066	[illegible]
"D"	Std.	.3093	N/A	.3082	N/A	.3080	.3006	.3081	.3007	.3085	.3013	.3086	.3009	N/A	.3004	N/A	.3009	N/A	.3007	N/A	N/A	.3067	N/A
1010	Lo-IX	N/A	N/A	N/A	N/A	N/A	.3061	N/A	.3058	N/A	.3054	N/A	.3056	N/A	.3054	N/A	.3053	N/A	.3049	N/A	.3054	N/A	.3045
1011	Lo-IX	.3111	N/A	.3106	N/A	.3107	.3043	.3107	.3042	.3107	.3043	.3106	.3045	.3105	.3045	.3104	.3041	.3104	.3038	.3104	.3036	N/A	.3030
5015	Hi-IX	.3116	N/A	.3113	N/A	.3113	.3054	.3112	.3052	.3112	.3055	.3112	.3055	.3112	.3054	.3111	.3051	.3110	.3049	.3110	.3051	N/A	.3033
5016	Hi-IX	.3114	N/A	.3109	N/A	.3110	.3045	.3109	.3046	.3108	.3049	.3107	.3044	.3108	.3043	.3108	.3041	.3107	.3042	[illegible]	.3041	N/A	.3028
1007	Lo-IX	.3112	N/A	.3109	N/A	.3109	.3053	.3108	.3050	.3107	.3057	.3106	.3058	.3104	.3056	.3103	.3051	.3102	.3055	.3102	.3054	N/A	.3054
1009	Lo-IX	.3115	N/A	.3113	N/A	.3113	.3063	.3112	.3061	.3110	.3055	.3110	.3054	.3110	.3047	.3110	.3045	.3099	.3043	.3097	.3049	N/A	.3034
5001	Hi-IX	.3116	N/A	.3112	N/A	.3111	.3057	.3111	.3057	.3110	.3057	.3111	.3066	.3110	.3063	.3109	.3066	.3109	.3067	.3109	.3066	N/A	[illegible]
5002	Hi-IX	.3111	N/A	.3109	N/A	.3108	.3046	.3108	.3048	.3107	.3047	.3107	.3048	.3107	.3045	.3107	.3041	.3107	.3044	[illegible]	[illegible]	[illegible]	.3032
2440	Lo-IX	.3112	N/A	.3110	N/A	.3109	.3046	.3107	.3043	.3106	.3040	.3103	.3035	.3103	.3032	.3102	.3029	.3100	.3030	[illegible]	.3027	N/A	.3034
1006	Lo-2X	.3112	N/A	.3109	N/A	.3108	.3055	.3106	.3048	.3105	.3044	.3103	.3054	.3100	.3041	.3097	.3048	.3097	.3037	[illegible]	[illegible]	N/A	N/A
5003	Hi-2X	.3110	N/A	.3104	N/A	.3104	.3035	.3103	.3034	.3103	.3035	.3103	.3033	.3101	.3027	.3096	.3030	.3095	.3041	N/A	.3047	N/A	N/A
5004	Hi-2X	.3109	N/A	.3106	N/A	.3104	.3050	.3102	.3045	.3101	.3051	.3101	.3049	.3098	.3047	.3095	.3044	.3094	.3042	[illegible]	N/A	N/A	N/A

*- Measurement made 2" from muzzle. **- Measurement made 1½" from muzzle.

Calibration points: For grooves: .30300" and .30946" No calibration ring (infinity): .3117"

For lands: .2995" and .3015" No calibration ring (infinity): Off scale (above .3070")

NOTE: ALL READINGS ABOVE THE UPPER CALIBRATION POINTS (.30946" and .3015" respectively) ARE APPROXIMATE (Use only for comparison).

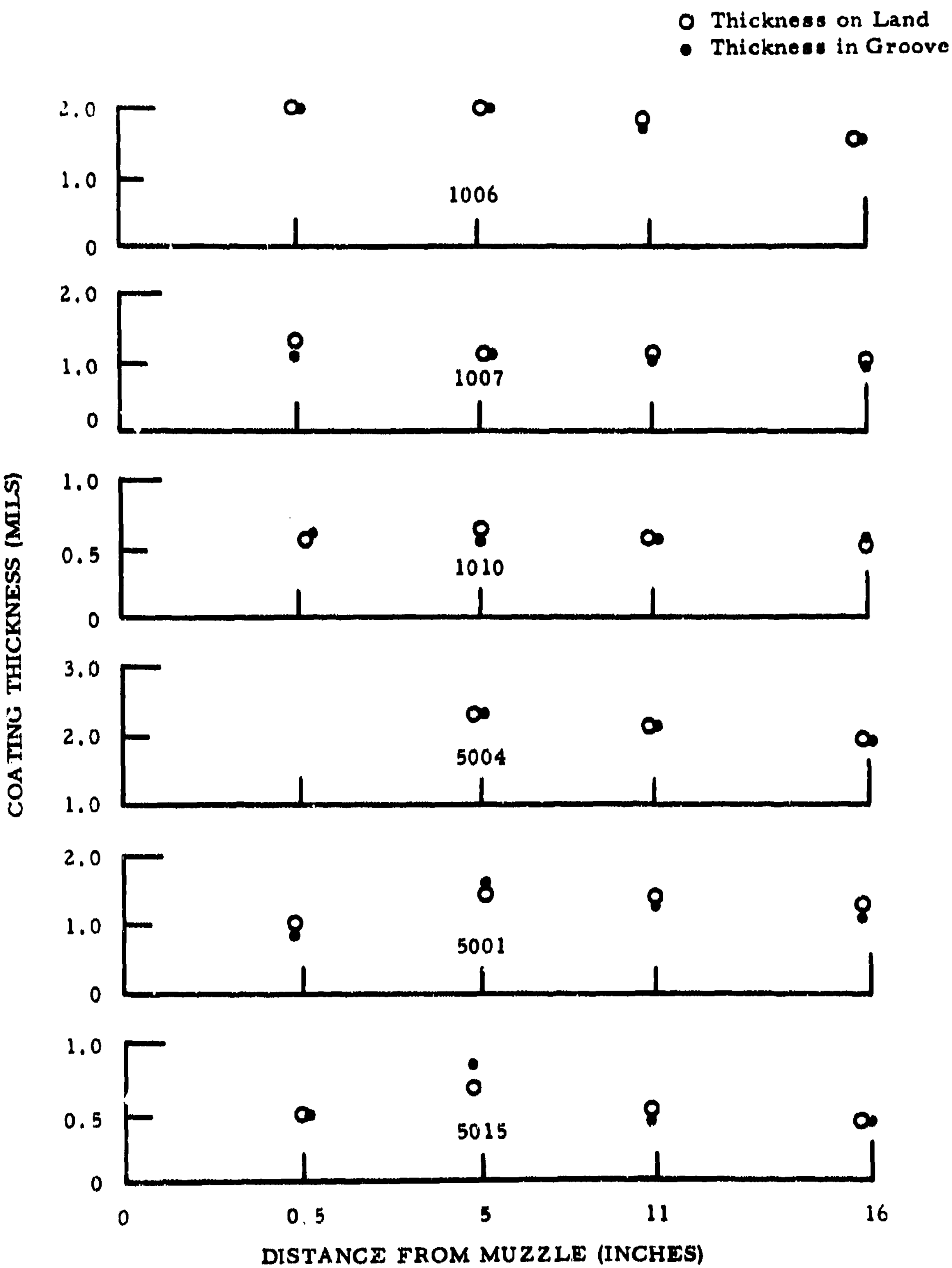


Figure 17 Coating Thickness Profiles from Tested Barrels

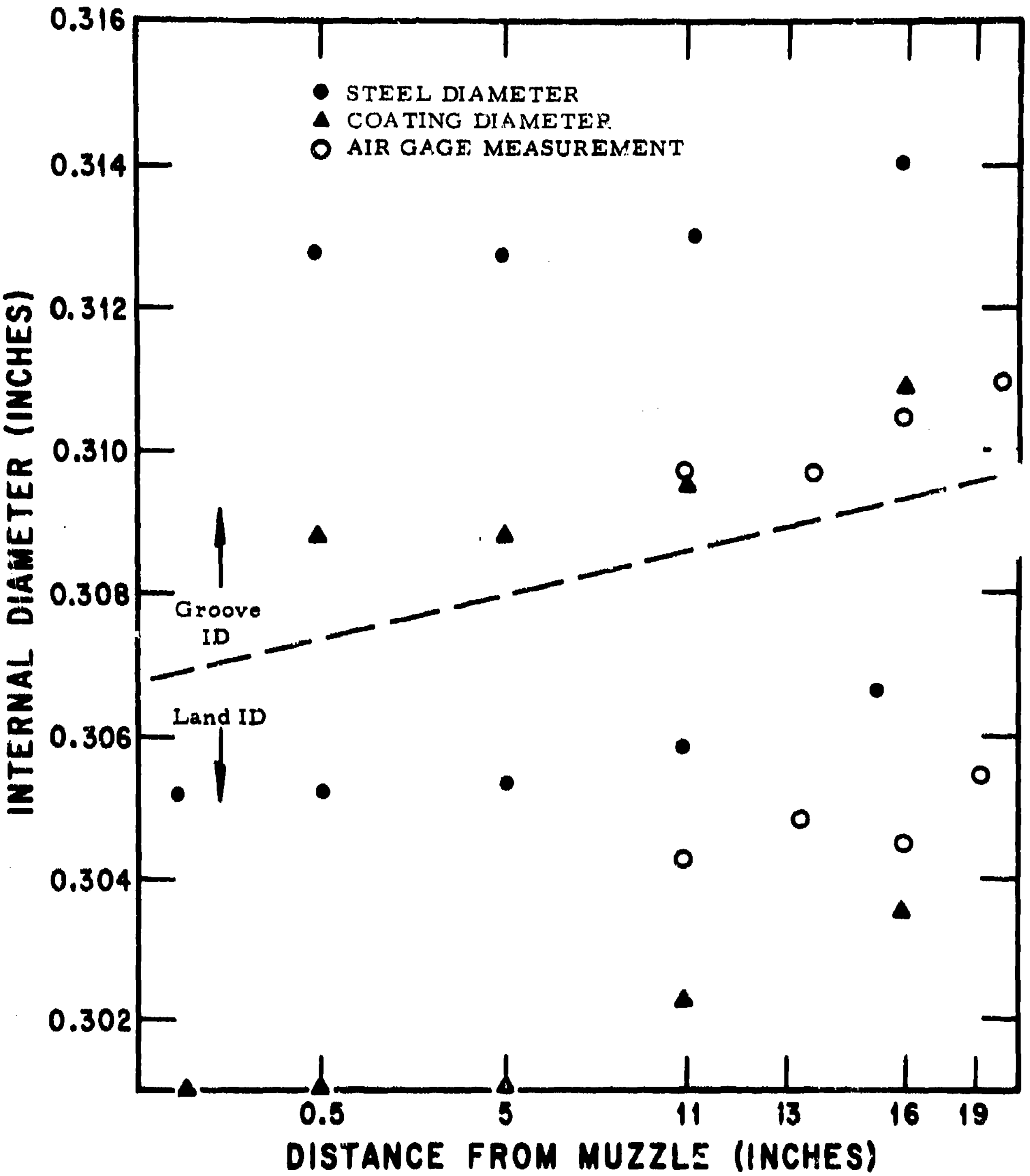


Figure 18(a) Diameters of Barrel 1006

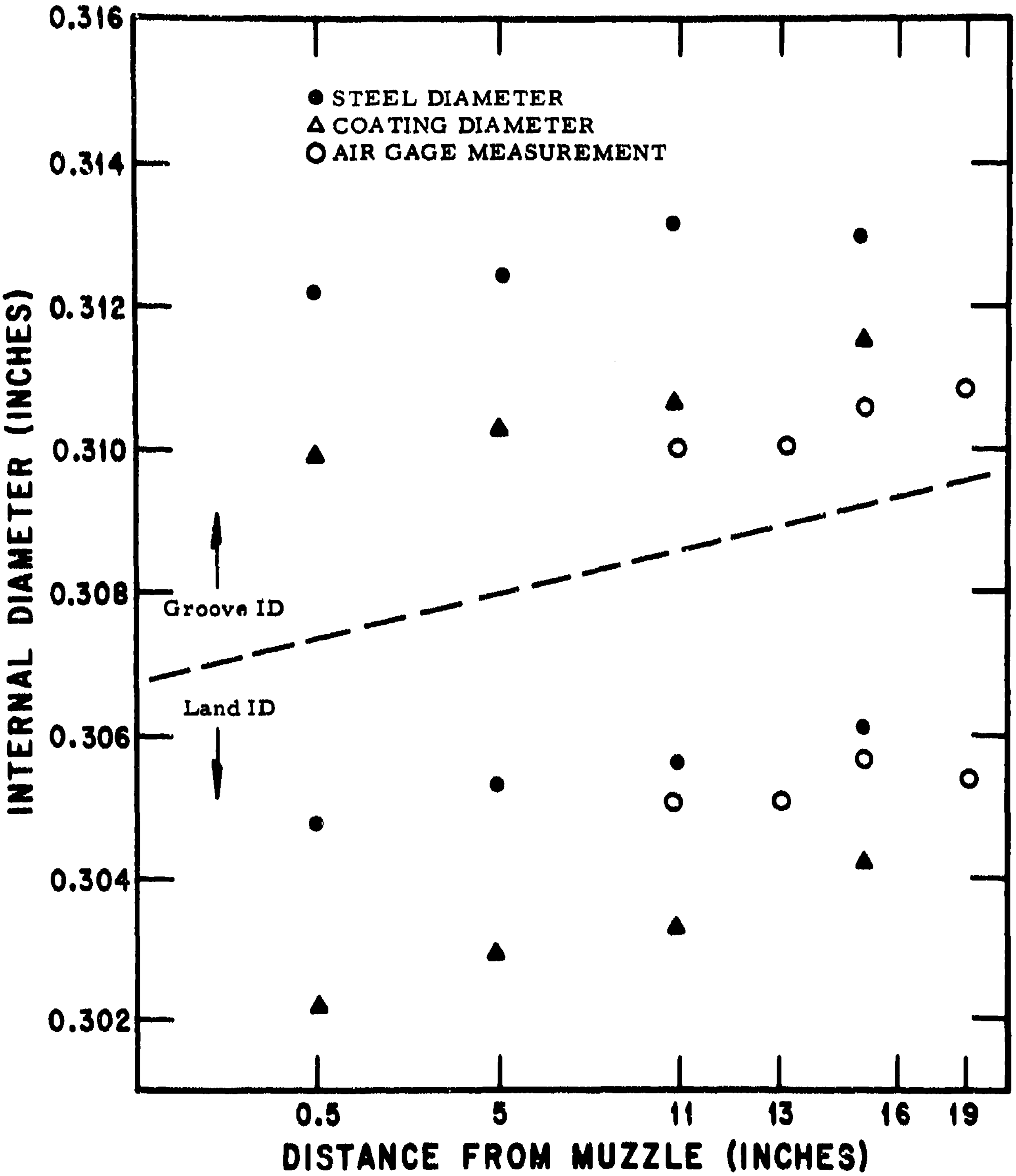


Figure 18(b) Diameters of Barrel 1007

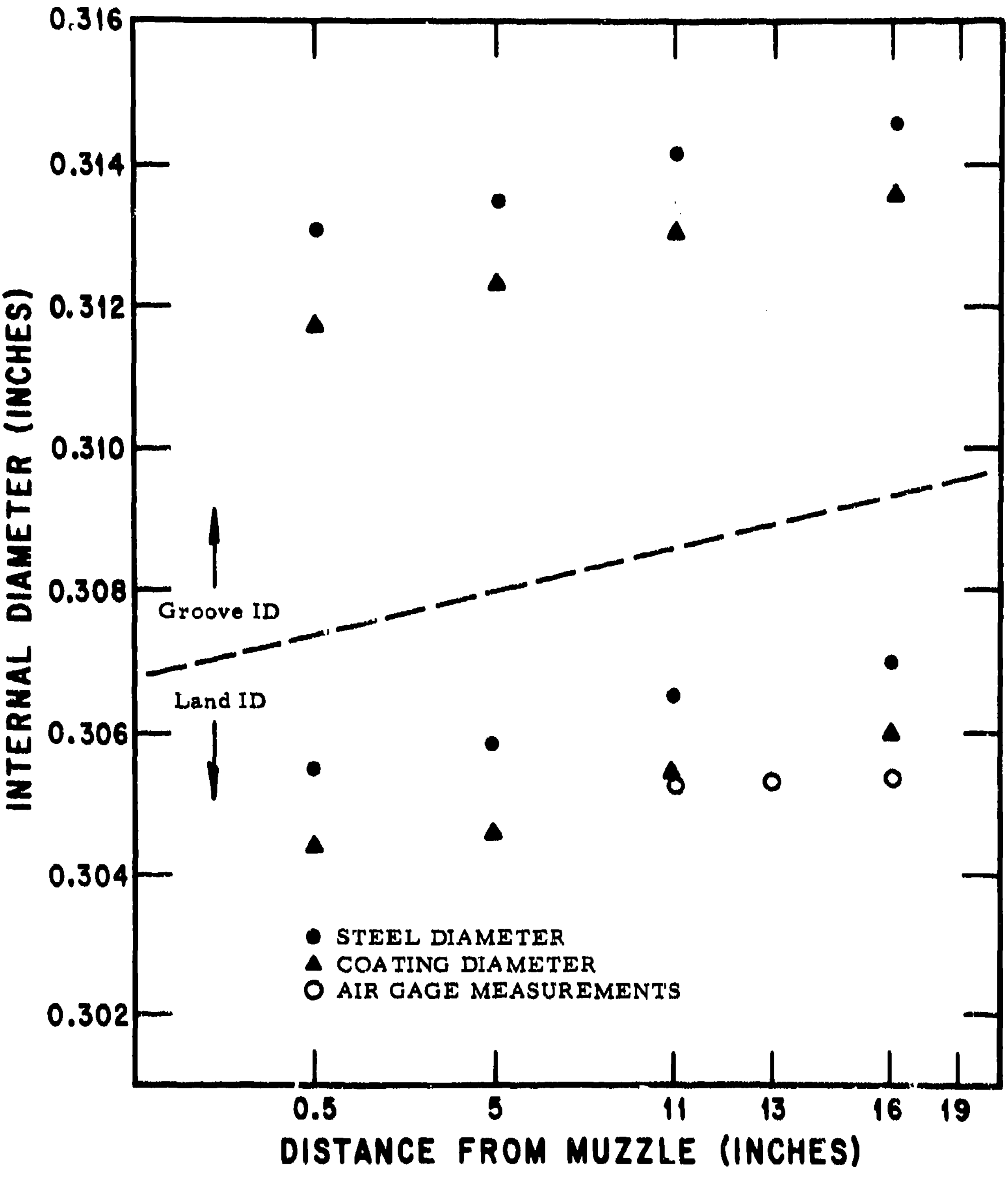


Figure 18(c) Diameters of Barrel 1010

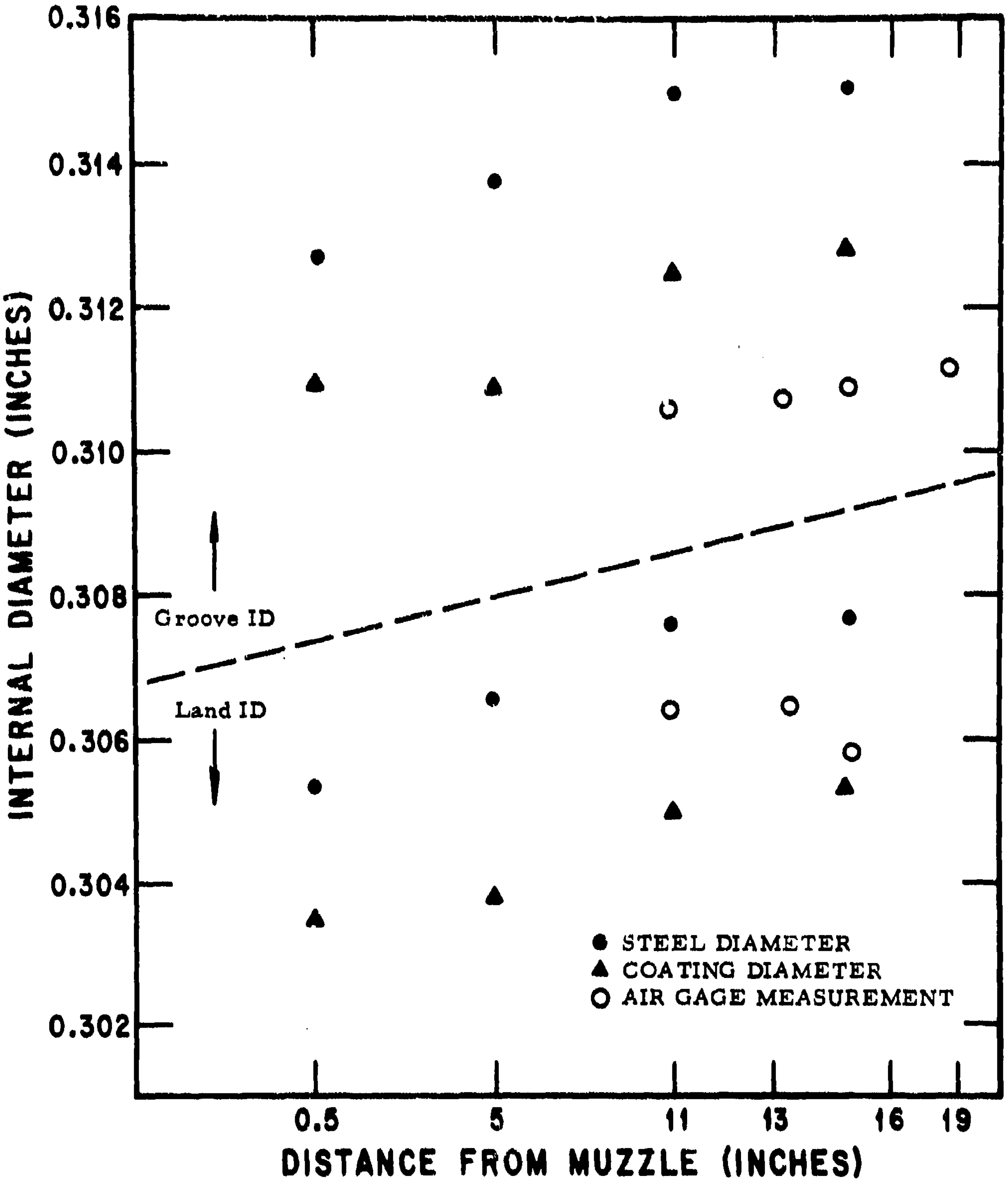


Figure 18(d) Diameters of Barrel 5001

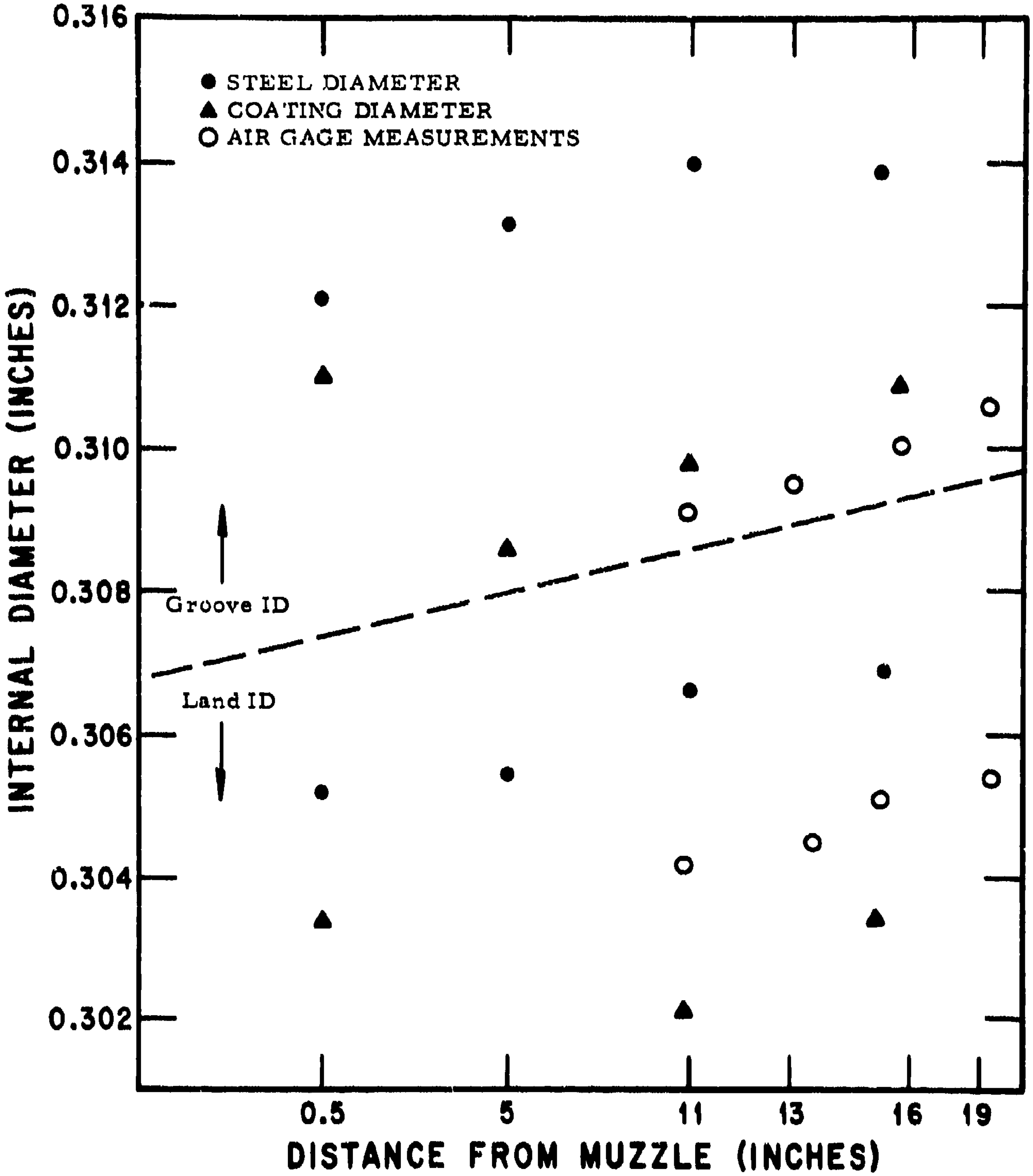


Figure 18(e) Diameters of Barrel 5004

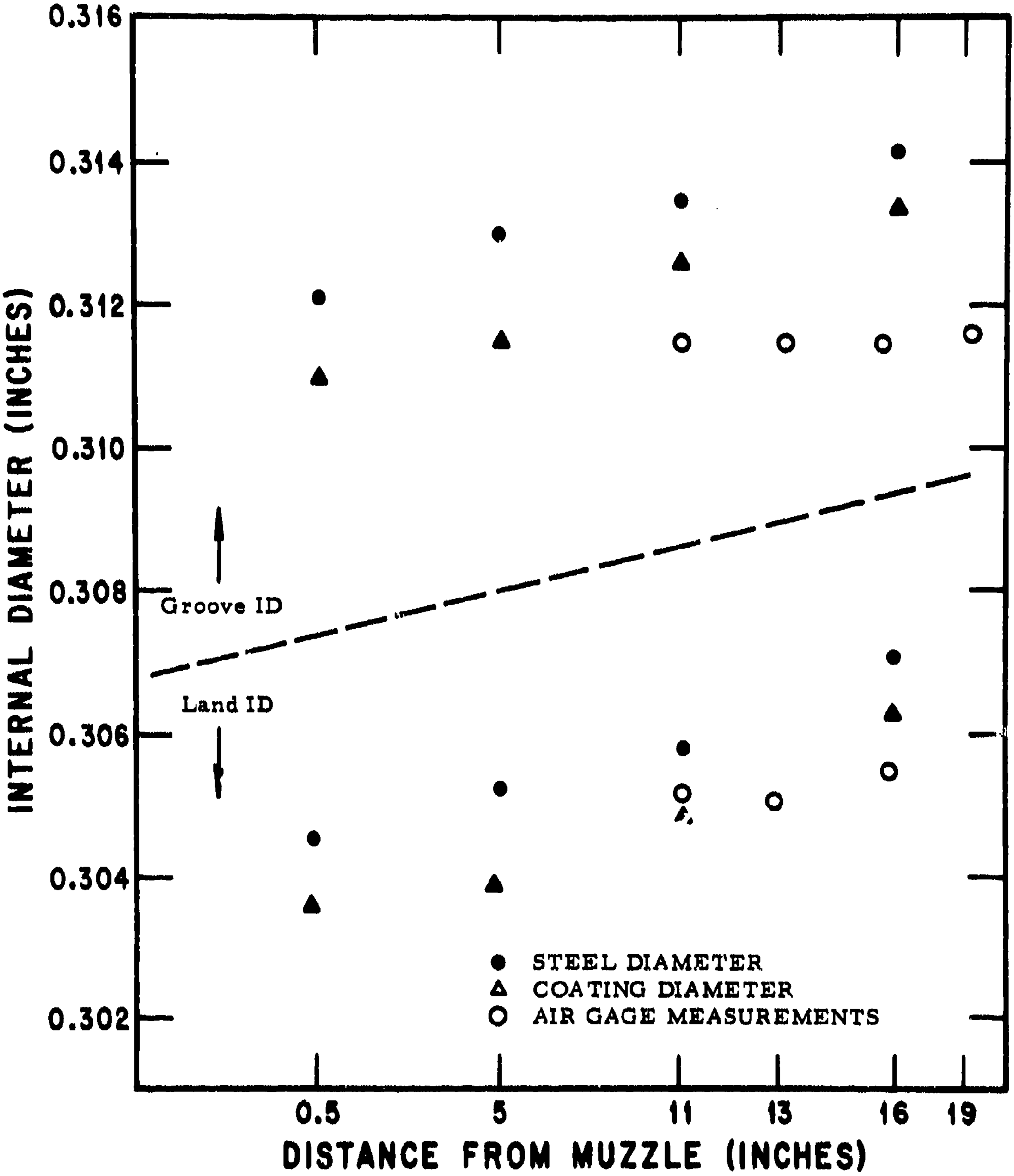


Figure 18(f) Diameters of Barrel 5015

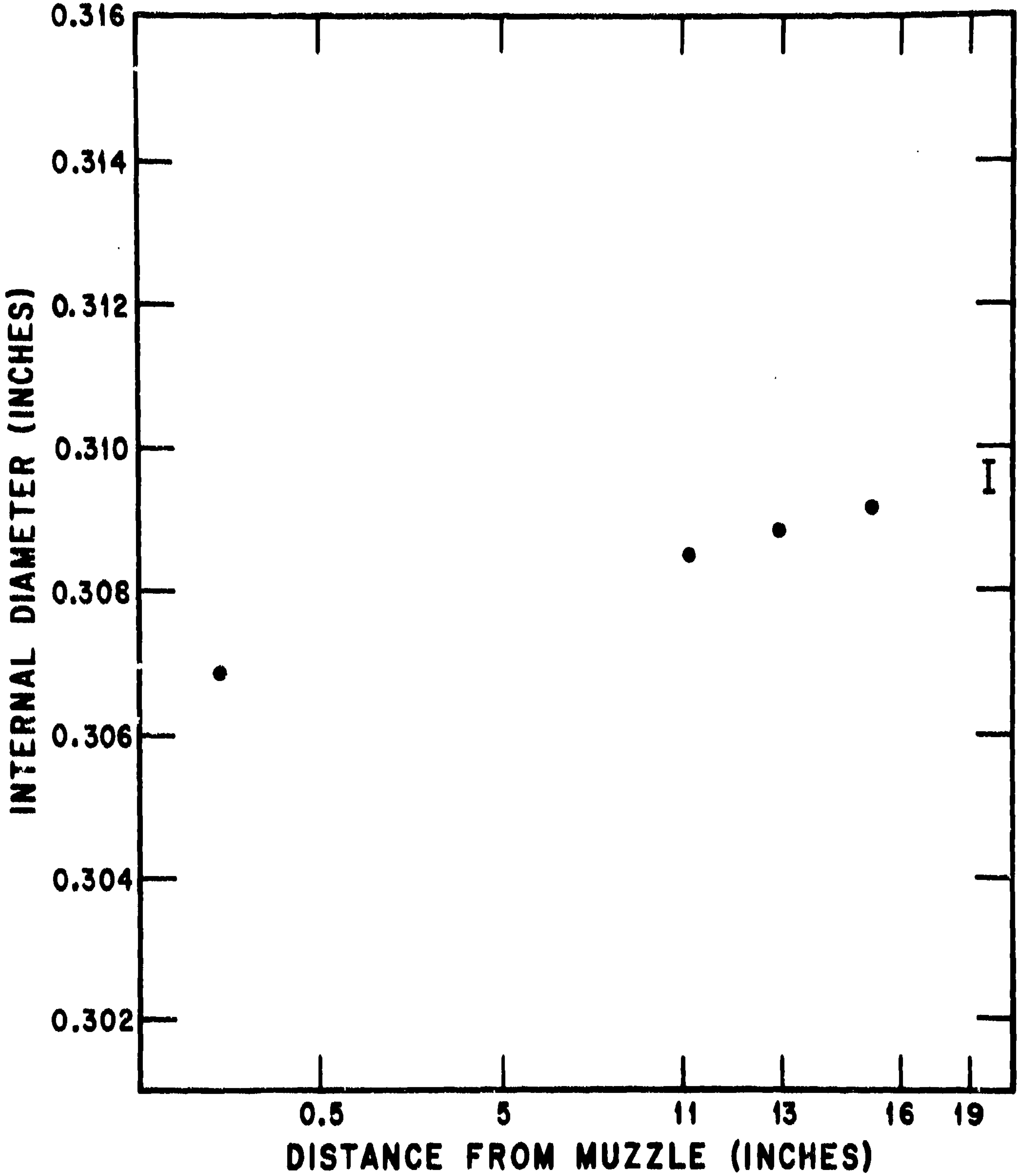


Figure 18(g) Diameter of Standard Barrel B
(Air gage measurements made by the Air Force)

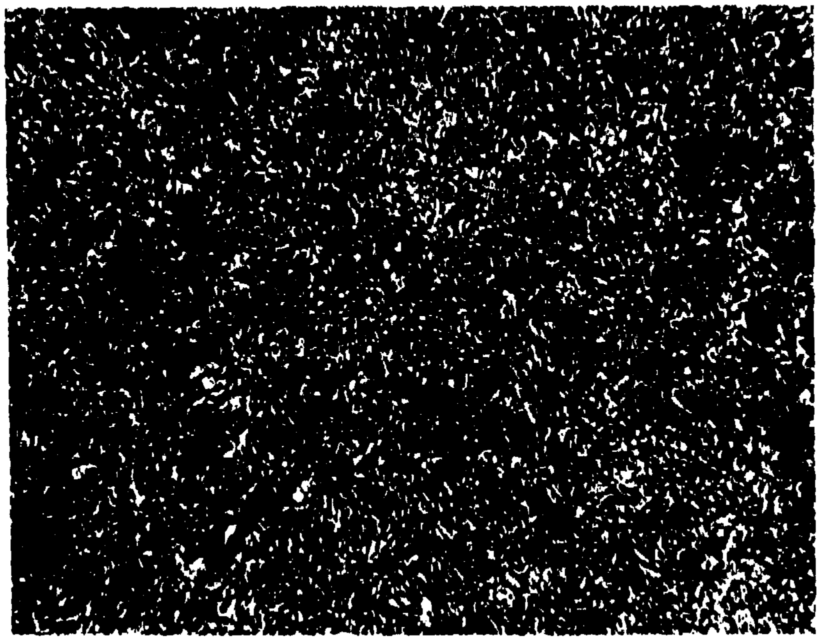


Figure 19 As-Received Mil-S-11595 Cr-Mo-V Gun Barrel Substrate Material (500X)

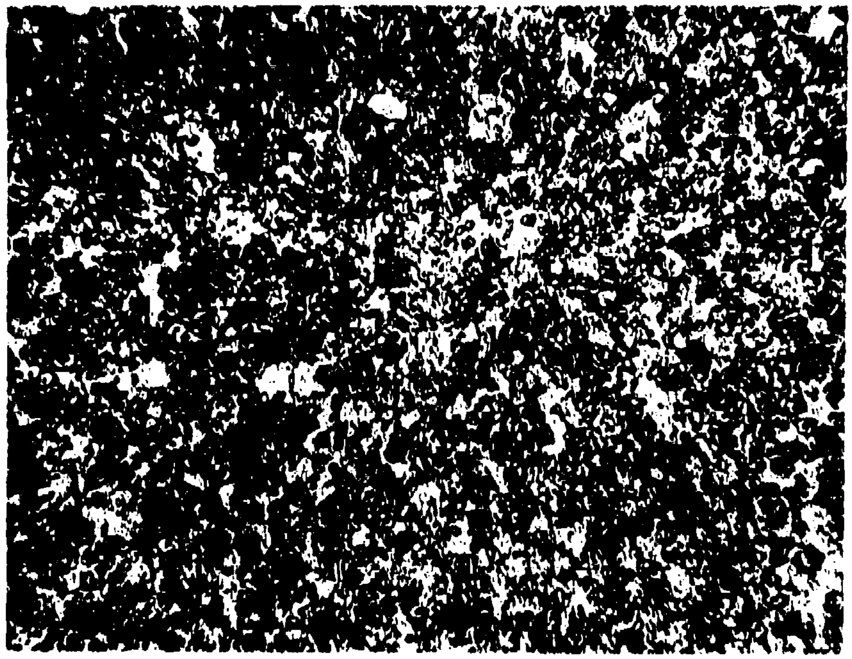


Figure 20 As-Coated Low Temperature Process Mil-S-11595 Cr-Mo-V Gun Barrel Substrate Material, Run No. 2240. (500X)

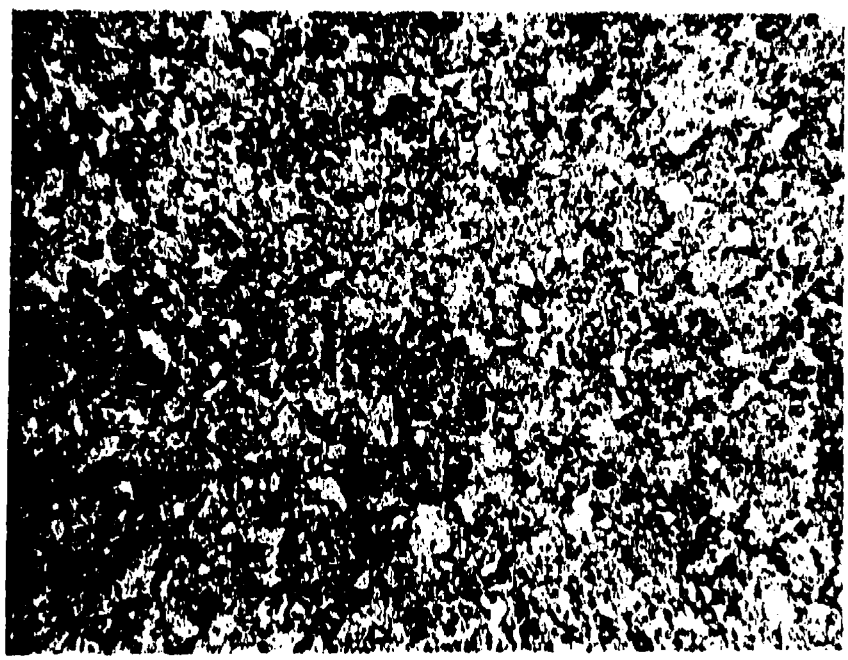


Figure 21 Heat Treated and Tempered Low Temperature Process Mil-S-11595 Cr-Mo-V Gun Barrel Substrate Material, Run No. 2240. (500X)

hardening schedules were considered to restore substrate hardness and metallurgical condition, and austenitizing the substrate at 1550°F, followed by tempering at 1000°F, was selected. A final hardness of R_c30-35 and good metal ductility were obtained.

Figure 21 shows a cross section of low temperature coated substrate material after hardening. Some small ferritic islands are visible in a tempered martensitic-bainitic structure. This structure should provide desirable ductility and yield strength properties for subsequent testing. Replication of barrels before and after hardening, as well as examination of microsections, shows the excellent adherence of the coating to a hardened and tempered substrate, even after a severe bend test. Figure ' is a photograph of the ID of a coated and tempered barrel after a 90° bend about the OD, showing adhesion and substrate ductility.

Barrels coated using the high temperature process have typical hardness values of R_c31-36 because the coating temperature is above the isothermal anneal temperature discussed above. At this higher temperature the substrate is austenitized during the coating cycle. The subsequent relatively slow cooling rate leaves the steel in a normalized condition. High temperature barrels are then tempered at a low temperature after coating. Figures 23 and 24 show the high temperature coated substrate structure before and after the tempering cycle.

The substrate structure of these barrels should be similar to that of the two barrels tested prior to the start of the program and so should be satisfactory for test firing. However, to further verify the acceptability of the high temperature barrels, bend tests were performed. The substrate ductility and coating adhesion are evident in Figure 25; this barrel section has been bent 100° about the OD with no substrate fracture or coating loss.

D. Economic Considerations

The economic aspects of both the high and low temperature processes for depositions carried out in the present reactor systems have been considered in an initial evaluation. The calculations are of value only in

Figure 22 View of ID Portion of Low Temperature Titanium Carbonitride Gun Tube Section Which Has Been Bent ~ 90° Around the OD. This view shows good metal ductility and excellent coating adhesion (1X).

Figure 23 As-Coated High Temperature Process Mil-S-11595 Cr-Mo-V Gun Barrel Substrate Material, Run No. 120260. (500X)

Figure 24 Tempered High Temperature Process Mil-S-11595 Cr-Mo-V Gun Barrel Substrate Material, Run No. 120260. (500X)

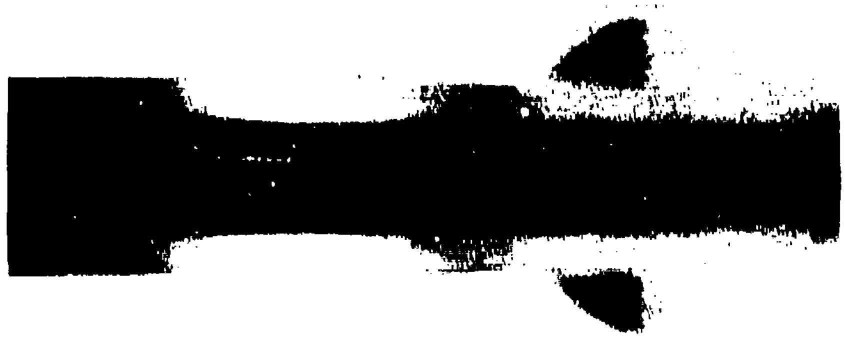


Figure 25 View of ID Portion of High Temperature Titanium Carbonitride Gun Tube Section Which Has Been Bent ~ 100° Around the OD. This view shows good metal ductility and excellent coating adhesion. (2X)

establishing a single point of laboratory-scale costs from which projections can be made regarding production-scale costs. Processing considerations for both processes are given in Table IX, and a breakdown of material costs for the low and high temperature processes is given in Tables X and XI, respectively.

The very low material costs for both processes, between \$0.15 and \$0.40, indicate potential for an attractive cost level for large quantity production. Projection of the production costs was done by assuming that the labor costs would be a major, but predictable, proportion of production costs. Based on assumptions of an improved pilot system which would increase production and decrease labor per barrel, a plating cost projection was made using ratios of materials, overhead, and amortization to labor, similar to an automatic zinc plating economic model.

Table XII shows the model, which indicates that a total cost of \$7.90/barrel for the coating is possible assuming development of ten-barrel batch type pilot reactors with an eight hour turn-around time. Such a turn-around time would allow an operator to run two such reactors (requiring only periodic checks during the run cycle to insure proper flows, etc.) and prepare barrels for subsequent runs during the run cycles.

Table IX

Process Considerations

	Low Temperature	High Temperature
Pretreatment Requirements for Barrels		
a. Operations	Degrease and glass bead peen barrel	Wire brush outside of barrel
	Etch with Fidelity 161 descale, Alkonox scrub, rinse and dry	Degrease barrel
b. Time	1 hour	0.75 hour
Reactor Preparation		
a. Operations	Load gun barrel and purge >10 min	Load gun barrel and purge > 10 min
	H_2 purge and heat to temperature	H_2 purge and heat to temperature
b. Time	1 hour	1.25 hours
Coating Cycle		
a. Reactant Costs		
1. H_2	$0.212 (etch & coat)	$0.069
2. Inert gas	$0.087	$0.004
3. $TiCl_4$	$0.012	$0.003
4. Anion	$0.018	$0.0002
b. Time	~5 hrs + 2 hrs cool-down	~4.5 hrs + 2.5 hrs cool-down
Reactor Clean-up		
a. Operations	Unload gun barrel, dismantle reactor and wash	Unload gun barrel and clean reactor, etc.
b. Time	1.5 hours	0.5 hour
Total Reactor Turn-around	10.5 hours	9.5 hours
Post-treatment requirements		
a. Operations	1550°F vacuum bake 0.75 hrs + 1000°F temperature and cool	300°F vacuum bake and cool
b. Time	1.5 hours + cool-down	0.75 hr + cool-down
Reactor Maintenance	Periodically replace quartz tubes and graphite sleeves	Periodically replace O-rings, rotoseals, and quartz tubes
Present Material Cost/Barrel	$0.40	$0.15
	$39.00	$34.50
	$39.40	$39.65

Table X

Low Temperature Process Material/Run Costs

Material	Use	Cost/Unit	Rate Used	Time Used (min)	Number of Units	Total Cost
H_2	Part Surface Preparation	$0.45/100 ft^3	0.128 ft^3/min	120	0.153	$0.069
H_2	Coating	$0.45/100 ft^3	0.177 ft^3/min	180	0.321	$0.143
Inert gas	Coating	$0.18/100 ft^3	0.221 ft^3/min	180	0.400	$0.072
$TiCl_4$	Coating	$0.22/lb	0.00029 lb/min	180	0.055	$0.012
Hydrocarbon	Coating	$0.62/lb	0.00016 lb/min	180	0.029	$0.018
Inert gas	Cool-down	$0.18/100 ft^3	0.070 ft^3/min	120	0.082	$0.015
Liquid solvents etchs, etc	Multiple	---	---	---	---	~$0.05

Table XI

High Temperature Process Material/Run Costs

Material	Use	Cost/Unit	Rate Used	Time Used (min)	Number of Units	Total Cost
H_2	Part Surface Preparation	$0.45/100 ft^3	0.044 ft^3/min	75	0.033	$0.0014
H_2	Coating	$0.45/100 ft^3	0.042 ft^3/min	210	0.080	$0.040
Inert gas	Coating	$0.18/100 ft^3	0.011 ft^3/min	210	0.023	$0.004
$TiCl_4$	Coating	$0.22/lb	0.000059 lb/min	210	0.0123	$0.0028
Hydro-carbon	Coating	$0.27/1000 ft^3	0.0028 ft^3/min	210	0.00059	$0.00016
H_2	Cool-down	$0.45/100 ft^3	0.034 ft^3/min	180	0.061	$0.028
Liquid solvents etch, etc.	Multiple	---	---	---	---	~$0.05

TABLE XII

Projected Costs of Titanium Carbonitride Coating of Gun Tube Inside Diameters Using Pilot Production System Facilities

(Assumptions:* Operator Running Two Ten-Barrel Batch-Type Reactors/Shift)

	% of Total Cost
Amortization and Maintenance	27.2
Materials	25.1
Labor (direct and indirect)	21.1
Overhead	26.6
	100.0

Labor @ \$3.00/hr	\$24/8 hrs to produce 20 barrels
Direct Labor Cost/Barrel	\$1.20
% of Labor Direct	72%
Total Cost/Barrel $\frac{\$1.20}{0.72 \times 0.211}$ =	\$7.90/barrel

* Model taken from Metals Handbook, 8th edition, Vol. 2, p. 422, "Costs of Cyanide Zinc Plating Sheet Steel Bases by Automatic Plating."

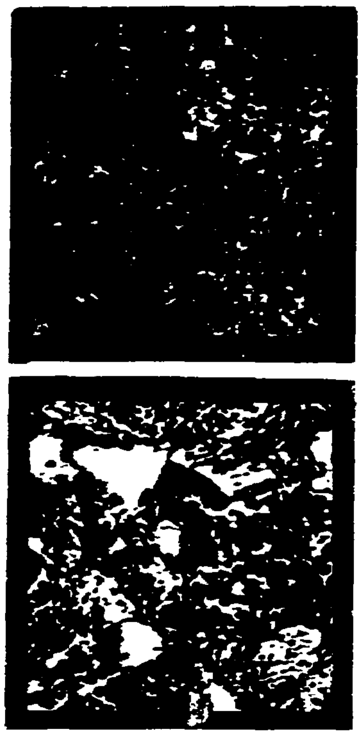
SECTION IV
TEST FIRING

A. Performance Results

Twelve coated barrels were shipped for test firing, four each from the two processes at three thickness levels. Figures 26(a) and (b) show microsections of the three thicknesses of coatings prepared by the low and high temperature process methods. The microstructure of the steel substrate appears relatively unaltered by the low temperature process; however, some grain growth is noted in the steel subjected to the high temperature coating process. As indicated in the photomicrographs, there appears to be a tendency toward slight roughening of the coating at thicker levels.

Preliminary performance measurements of velocity and accuracy were conducted at the 3246th Test Wing at Eglin Air Force Base, Florida. These test firing data for the coated barrels, given in Table XIII, showed decrease in both velocity and accuracy. Plug gage determination indicated a muzzle diameter that was oversize by several mils. The diameters of a number of the gun barrels being used in this program were examined at Texas Instruments by measuring cross sections of the barrels under a microscope. The results are summarized in Table XIV. Some of the steel diameters are displayed in the plots of Figure 27. Barrel No. 4, which was coated prior to the contract effort and subjected to test firing at General Electric Company, Burlington, Vermont, is representative of a barrel steel diameter in the "as-machined" state, since no metal was removed following the machining operation. The barrel steel diameter of the standard barrel from the same test is representative of a steel diameter prepared for chromium plating and shows metal removal from the as-machined state. Barrel 2530 is representative of a steel diameter after the metal removal step (prior to chromium plating) <u>and</u> during the chromium plate stripping process.

Data for some of the coated barrel diameters are displayed in the plot of Figure 28. Barrel 2530 has a designed coating thickness of 1 mil and shows that control of coating thickness is achieved. The chromium-plated barrel is the same as that in Figure 29 and is representative of a standard chromium-plated barrel.



Photomicrograph
of Steel

As Recieved

Hardness R_A 68

500X

Final Coated

Hardness R_A 66

500X

Photomicrograph
of Coatings

.002"

.001"

.0005"

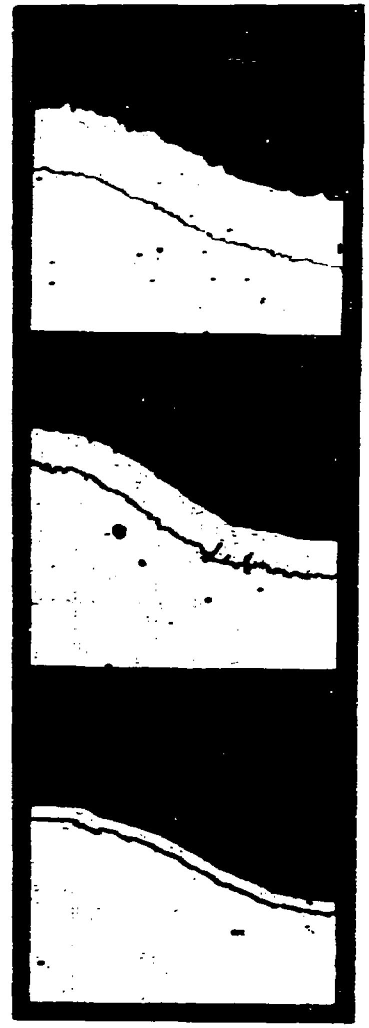


Figure 26(a) Barrels With Varied Thicknesses of Coating Prepared by High Temperature Process

Photomicrograph of Steel

As Received

Hardness R_A 68

500X

Final Coated

Hardness R_A 67

500X

Photomicrograph of Coatings

.002"

.001"

.0005"

Figure 26(b) Barrels With Varied Thicknesses of Coating Prepared by Low Temperature Process

TABLE XIII
PERFORMANCE DATA FROM TITANIUM CARBONITRIDE BARRELS

No.	TI S/N	CVD TEMP	CVD THICK	MFGR	GUN NO.	AVG. MUZZ. VEL (FPS)*	80% DISP. MILS (In.) X	80% DISP. MILS (In.) Y	YAW % 15	EXTRACTION OF CARTRIDGE	MUZZLE DIA Inches
A	STANDARD	--	---	H&R	1	2770	1.4	2.0	0.0	GOOD	0.297
B	STANDARD	--	---	H&R	1	2766	1.5	1.0	0.0	GOOD	0.297
C	STANDARD	--	---	H&R	2	2763	0.8	1.3	0.0	GOOD	0.299
D	STANDARD	--	---	H&R	2	2758	1.5	1.2	0.0	GOOD	0.297
10	1010	LOW	½ M	H&R	---	2696	5.0	4.2	5.0	POOR TO FAIR	
11	1011	LOW	½ M	H&R	---	2763	1.4	2.2	0.0	GOOD	
15	5015	HIGH	½ M	H&R	---	2659	5.4	8.0	25.0	GOOD	
16	5016	HIGH	½ M	H&R	---	2710	4.4	2.3	10.0	FAIR	
7	1007	LOW	1 M	H&R	1	2746	1.5	0.8	0.0	GOOD	0.302
9	1009	LOW	1 M	H&R	1	2684	4.6	3.7	0.0	GOOD	0.302
1	5001	HIGH	1 M	H&R	2	2622	4.8	7.5	25.0	POOR TO FAIR	0.303
2	5002	HIGH	1 M	TRW	2	2684	2.9	4.2	10.0	GOOD	0.305
0	244-C	LOW	2 M	H&R	1	2688	3.5	4.0	20.0	GOOD	0.302
6	1006	LOW	2 M	H&R	1	2709	2.7	2.7	10.0	FAIR	0.301
3	5003	HIGH	2 M	TRW	2	2725	4.6	3.1	15.0	VERY POOR	0.299
4	5004	HIGH	2 M	H&R	2	2684	6.2	8.9	25.0	VERY POOR	0.298

TABLE XIV

BARREL DIAMETER MEASUREMENTS

Barrel Number	Coating Thickness	DIAMETER OF STEEL Land	Groove	Land	Groove	DIAMETER OF COATING Land	Groove	Land	Groove	Process	Inches From Muzzle End
2310*	"1 mil"	.3070	.3147	.3075	.3145	.3050	.3130	.3055	.3130	L.T.	16
2530	"2 mil"	.3075	.3150	.3075	.3150	.3045	.3120	.3045	.3120	L.T.	16
2530	"2 mil"	.3058	.3130	.3055	.3130	.3020	.3090	.3015	.3090	L.T.	5
3150	"½ mil"	.3070	.3140	.3070	.3145	.3060	.3130	.3060	.3125	L.T.	16
3150	"½ mil"	.3053	.3125			.3040	.3115				5
1270216	"1 mil"	.3070	.3150	.3070	.3145	.3050	.3130	.3050	.3135	H.T.	16
1270266	"2 mil"	.3070	.3140	.3065	.3140	.3040	.3115	.3040	.3115	H.T.	16
1270321	"½ mil"	.3065	.3133	.3063	.3135	.3055	.3123	.3054	.3125	H.T.	16
No. 4 GE Test	".4 mil"	.307	.3095			-	.3085			H.T.	½
No. 4 GE Test	".4 mil"	.3078	.3103			-	.3095			H.T.	5
No. 4 GE Test	".4 mil"	.3015	.310			.2995	.3075			H.T.	11
Standard GE Test	"2 mils"	.3055	.311			-	.3076				½
Standard GE Test	Chromium	.3055	.3122			-	.309				5
Standard GE Test	Chromium	.3034	.311			.2997	.3075				11
2310*	"1 mil"	.3058	.313			.302	.309			L.T.	½
2310*	"1 mil"	.307	.314			.3035	.311			L.T.	11
3150	"½ mil"	.3058	.313			.3047	.3118			L.T.	½
3150	"½ mil"	.306	.313			.3044	.3114			L.T.	11

* From Warner Robbins

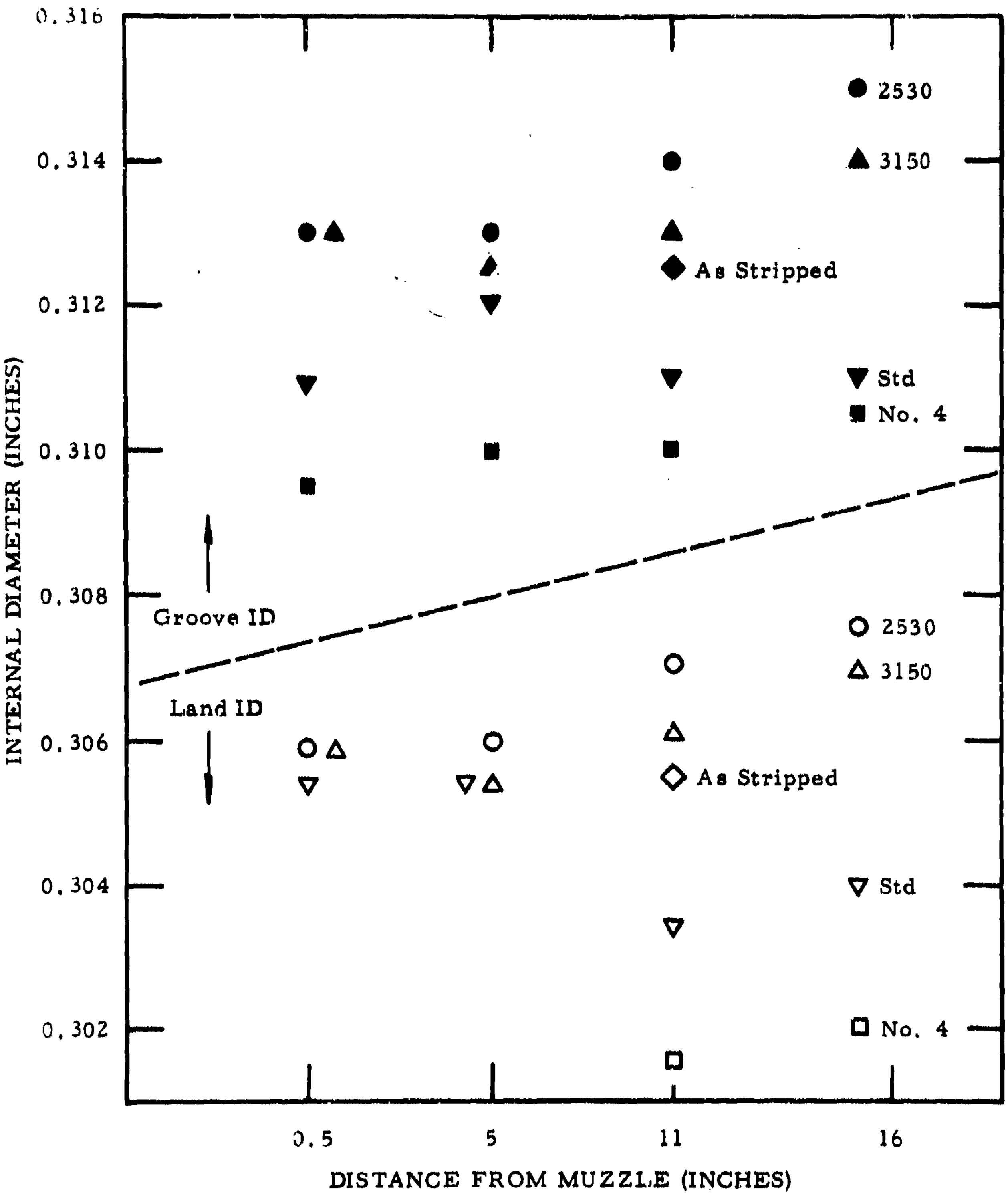


Figure 27 Steel Diameters of Barrels

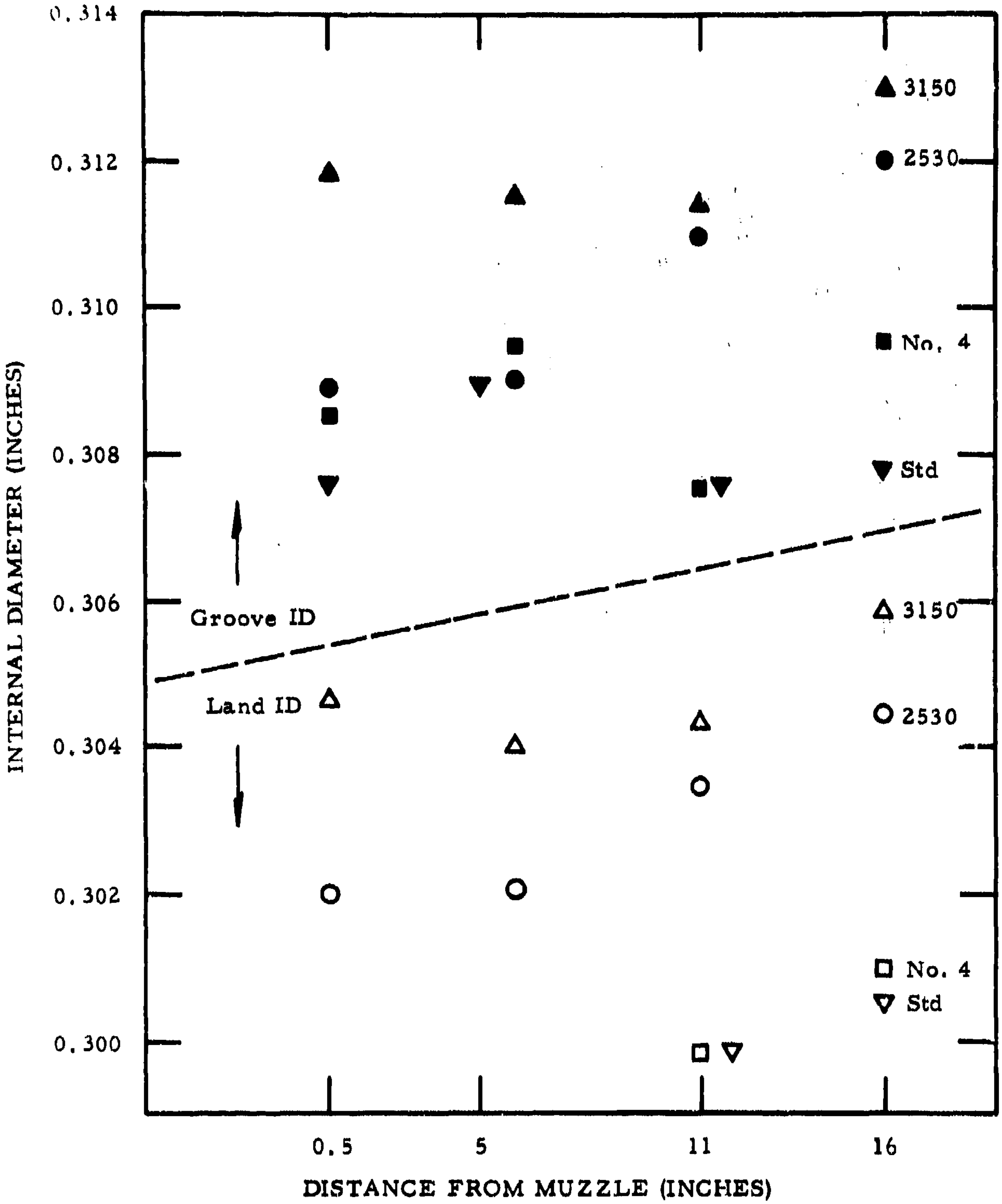


Figure 28 Coating ID of Barrels

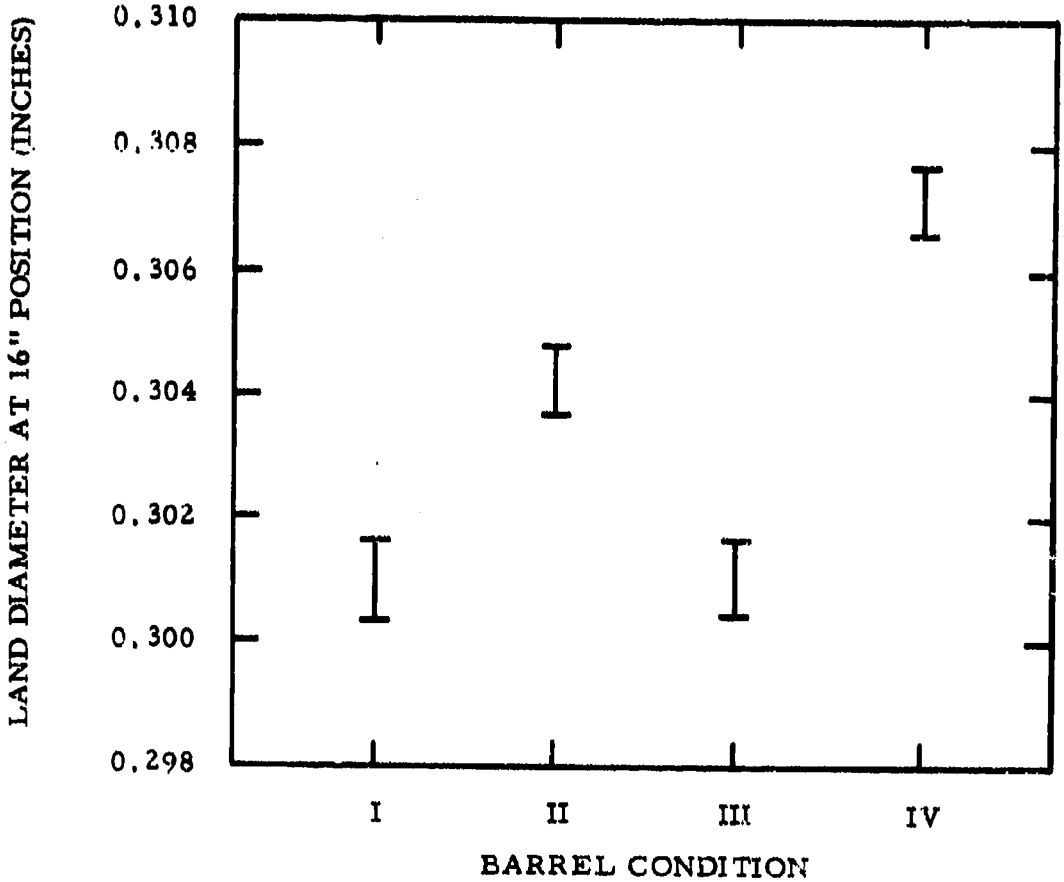


Figure 29 Summary of Barrel Diameter in Various Conditions:

I Steel As Machined

II Steel As Electropolished

III Chromium Plated

IV Steel After Chromium Removal

The groove and land steel diameters in the scrap barrels obtained for equipment set-up and the "good" barrels from the Warner Robbins Air Force Base stockpile exceed the diameter required to provide a coated barrel of the correct dimensions. Electropolishing to taper the barrel and to remove steel to allow for the chromium plating in the standard manufacturing process caused the oversized ID. Deplating to strip the chromium from barrels for this program removed a small amount of steel also. The diameter variations for several conditions are summarized in Figure 29.

Attempts to relate barrel preparation to performance were made by rank-ordering the barrels by velocity (Table XV), dispersion sum (Table XVI), and percent of yaw (Table XVII). A slight preference for the low temperature process seems evident from these tables, as well as from a table using the sum of the previous table rankings (Table XVIII). No mandate is given for either process or thickness.

Some difficulty in extracting the shell from the chamber of the coated barrels was noted, and examination of the brass showed many scratches due to coating roughness. A somewhat similar difficulty was encountered in earlier tests and was found to be caused by nodules built up on the coating during the deposition process. A chamber polish method, using diamond lapping paste, was devised to eliminate this problem.

As a result of the performance data collected on the twelve coated barrels and the data collected on inside diameter sizes, it was decided that testing should not proceed on those barrels and that barrels specially sized for the addition of the coating should be obtained for performance testing. Custom sized barrels* for testing were fabricated for Texas Instruments. These barrels were honed prior to coating to round the sharp corners on the lands. Barrels from this lot were coated by both the low and the high temperature processes for test firing.

The first gun set of special-size barrels shipped for testing consisted of the following:

---

* Barrels made by Aeronutronic Division of Philco-Ford.

TABLE XV

Barrels Ranked by Velocity

Velocity	Barrel Number	Temperature	Thickness (mils)
2763	1011	L*	1/2
2746	1007	L	1
2725	5003	H†	2
2710	5016	H	1/2
2709	1006	L	2
2696	1010	L	1/2
2688	2440	L	2
2684	1009	L	1
2684	5002	H	1
2684	5004	H	2
2659	5015	H	1/2
2622	5001	H	1

TABLE XVI

Barrels Ranked by Dispersion (x+y)

Dispersion	Barrel Number	Temperature	Thickness (mils)
1.5 + 0.8	1007	L*	1
1.4 + 2.2	1011	L	1/2
2.7 + 2.7	1006	L	2
4.4 + 2.3	5016	H†	1/2
2.9 + 4.2	5002	H	1
3.5 + 4.0	2440	[illegible]	2
4.6 + 3.1	5003	H	2
4.6 + 3.7	1009	L	1
5.0 + 4.2	1010	L	1/2
4.8 + 7.5	5001	H	1
5.4 + 8.0	5015	H	1/2
6.2 + 8.9	5004	H	2

* L indicates the low temperature coating process was used.

† H indicates the high temperature coating process was used.

TABLE XVII

Barrels Ranked by Yaw

Yaw	Barrel Number	Temperature	Thickness (mils)
0	1011	L*	1/2
0	1007	L	1
0	1009	L	1
5.0	1010	L	1/2
10.0	5016	H+	1/2
10.0	5002	H	1
10.0	1006	L	2
15.0	5003	H	2
20.0	2440	L	2
25.0	5015	H	1/2
25.0	5001	H	1
25.0	5004	H	2

TABLE XVIII

Barrels Ranked by Sum of Ranking

Rank Sum	Barrel Number	Temperature	Thickness (mils)
4	1011	L*	1/2
5	1007	L	1
13	5016	H+	1/2
15	1006	L	2
18	5003	H	2
19	1009	L	1
19	1010	L	1/2
20	5002	H	1
23	2440	L	1
32	5015	H	1/2
33	5001	H	1
34	5004	H	2

* L indicates the low temperature coating process was used.

+ H indicates the high temperature coating process was used.

No. 1371 "1 mil" coating, low temperature process
No. 1381 "2 mil" coating, low temperature process
No. 1391 "2 mil" coating, low temperature process
No. 1401 "1 mil" coating, low temperature process

After the coatings were applied, the barrel chambers were lapped with diamond paste to remove any nodules which would hinder cartridge removal Silicone replications of the barrels were smooth enough to have a shine, suggesting a considerably improved ID surface in the barrels.

This set of gun barrels, with 2 mil and 1 mil coatings applied by the low temperature process, performed only 50% as well in the test firing as chromium-plated barrels.

A second set of low temperature coated barrels, consisting of two special size barrels having "3/4 mil" coating and one barrel (1011) from the Eglin test having a "1/2 mil" coating, was shipped to the Naval Weapons Laboratory for testing. The latter barrel was previously chromium-plated, only slightly oversized. This barrel had given good velocity and accuracy data at Eglin, and it was included to determine if the specially machined barrels were faulting the performance tests. It failed sooner than the other barrels in this test, indicating that the use of the specially machined steel barrels is apparently not responsible for the early failure of the coated barrels. The "3/4 mil" barrel failed after approximately the same number of rounds as the barrels in the first set.

B. Post-Firing Barrel Analysis

Examination of cross sections of the barrels (see Table XIX) indicates a softer steel substrate than desired, which may have been a significant factor in the reduced performance. Where the coating was retained, its quality appears good; little degradation can be found in the photomicrographs or in the hardness (also given in Table XIX). Photomicrographs of the tested barrels are shown in Figures 30 through 33. In the breech end of the barrel, where the coating is absent, surface degradation and cracking are as expected for an unplated steel barrel. The midsection of each barrel shows loss of

TABLE XIX

Analysis of Fired Barrels

Barrel	Position	Coating Thickness (mils)	Coating Hardness KHN_{50}	Steel ID Groove	Steel Hardness R_c	Steel OD	Manufacturer
1381	1/2	1.6	2377	0.312	27	0.619	Ford
	5	1.5		0.312	24		
	11	1.3		0.311	22-24		
	16	-		0.315	22-24		
	21	1.5			28-30		
1401	1/2	1.4	2196	0.311	26	0.619	Ford
	5	1.3		0.3125	22-24		
	11	1.3		0.312	22-24		
	16	1.1		0.312	18		
	21	.7			21-23		
1483	1/2	.8	2101	0.312	27-28	0.618	Ford
	5	.8		0.312	25-26		
	11	.7		0.3125	26		
	16	.6		0.312	26-27		
	21	.4			28-32		
1011	1/2	.6	2056	0.312	29-30	0.6185	TRW
	5	.6		0.312	27-28		
	11	.6		0.312	28-30		
	16	.4		0.312	28-32		
	21	.4			31-32		
27155 (Unfired)	1/2				35.5-36	0.619	TRW
	5				33-35		
	11				34.5		
	16				34-35.5		
	21				34-34.5		

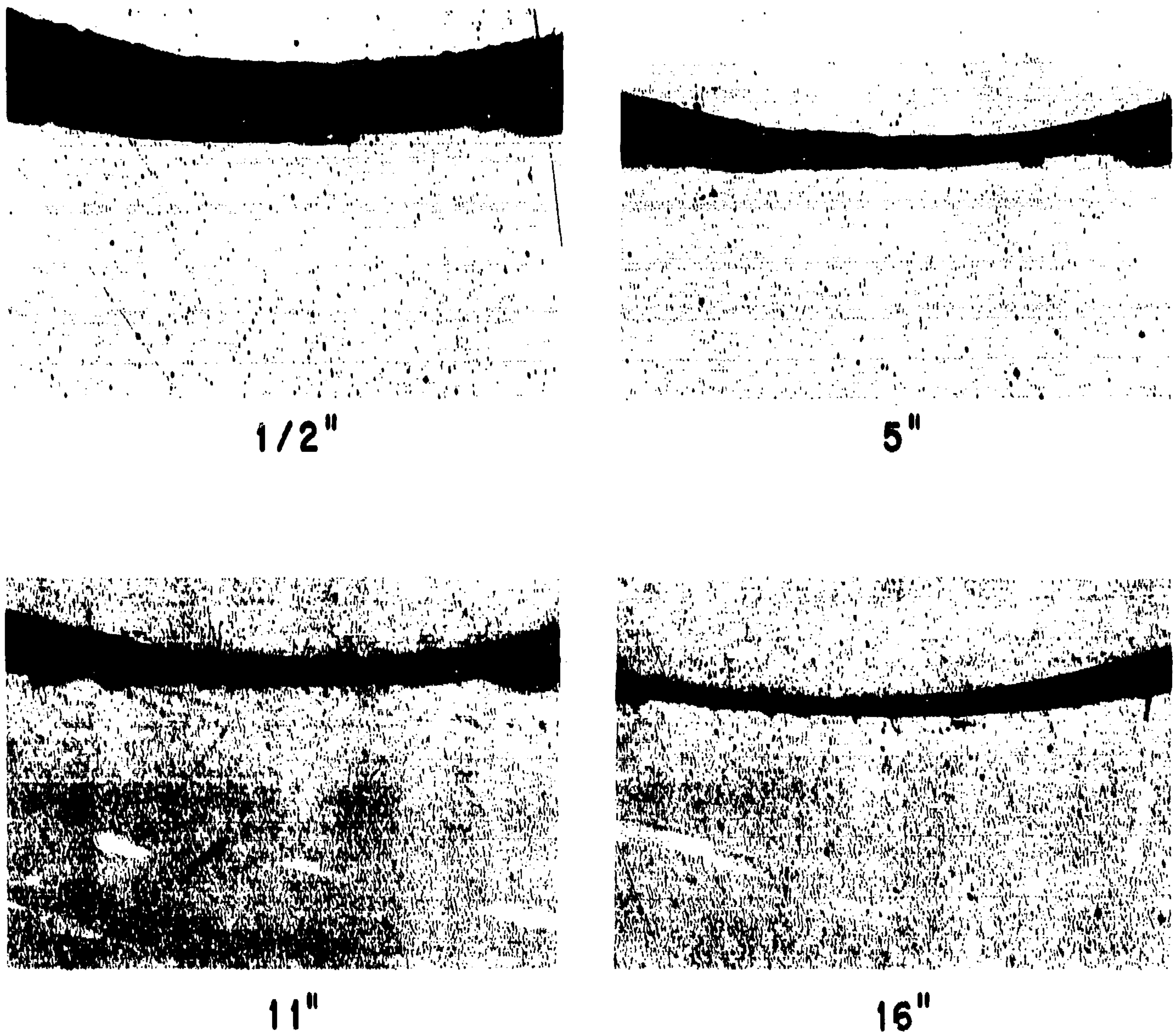


Figure 30 Photomicrographs of Lands from Tested Barrel 1011. (50X)

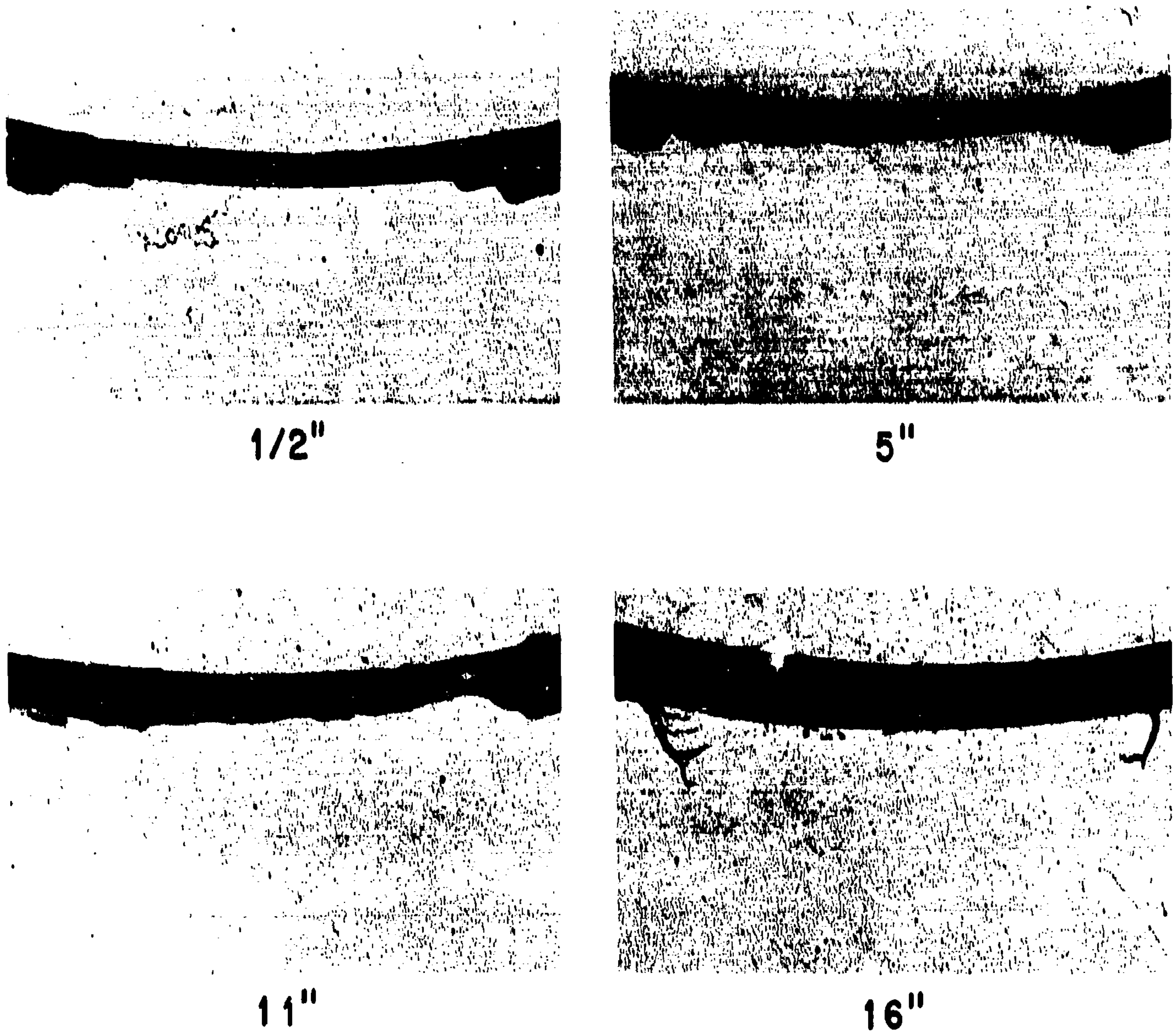


Figure 31 Photomicrographs of Lands from Tested Barrel 1381. (50X)

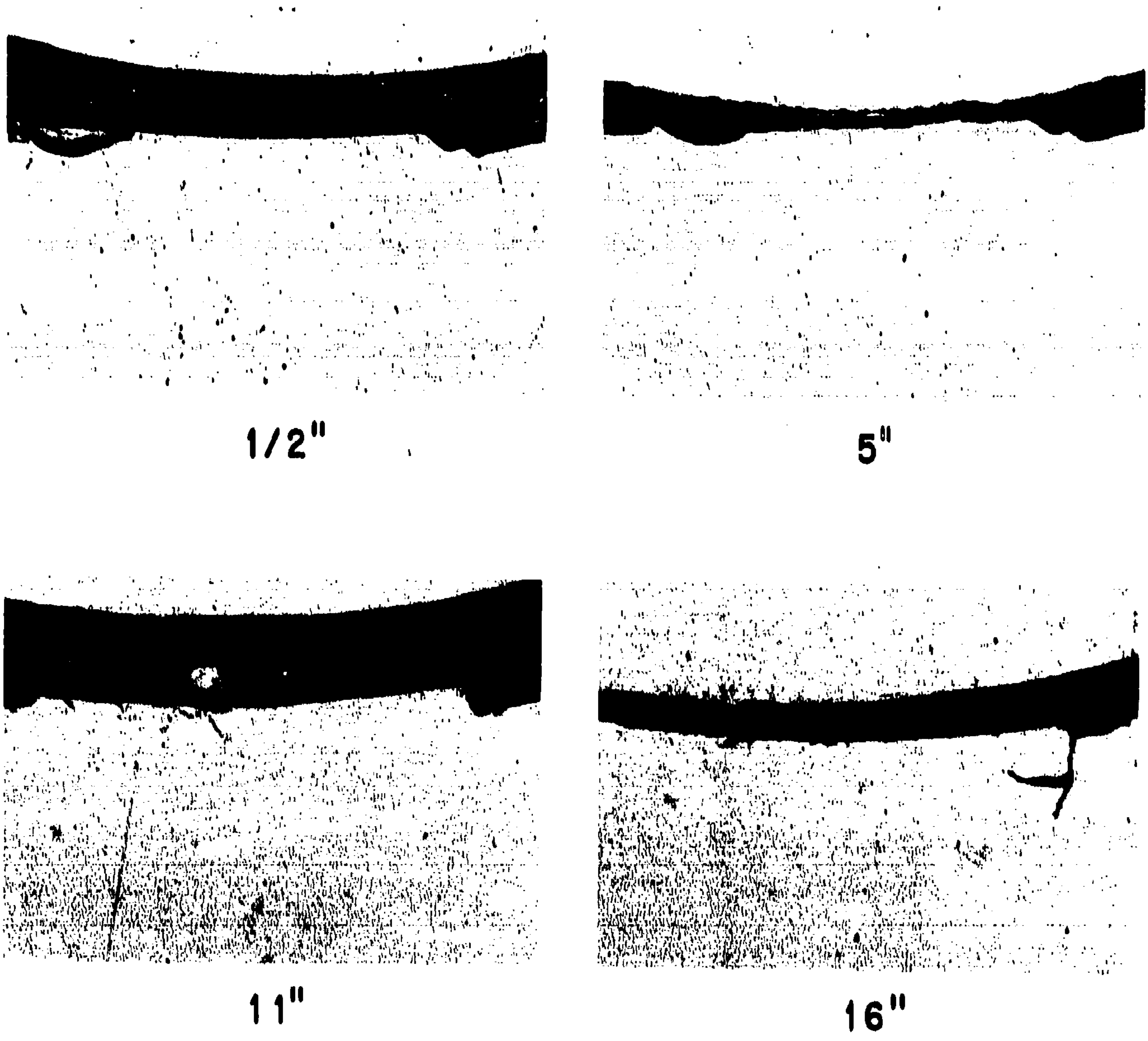


Figure 32 Photomicrographs of Lands from Tested Barrel 1401. (50X)

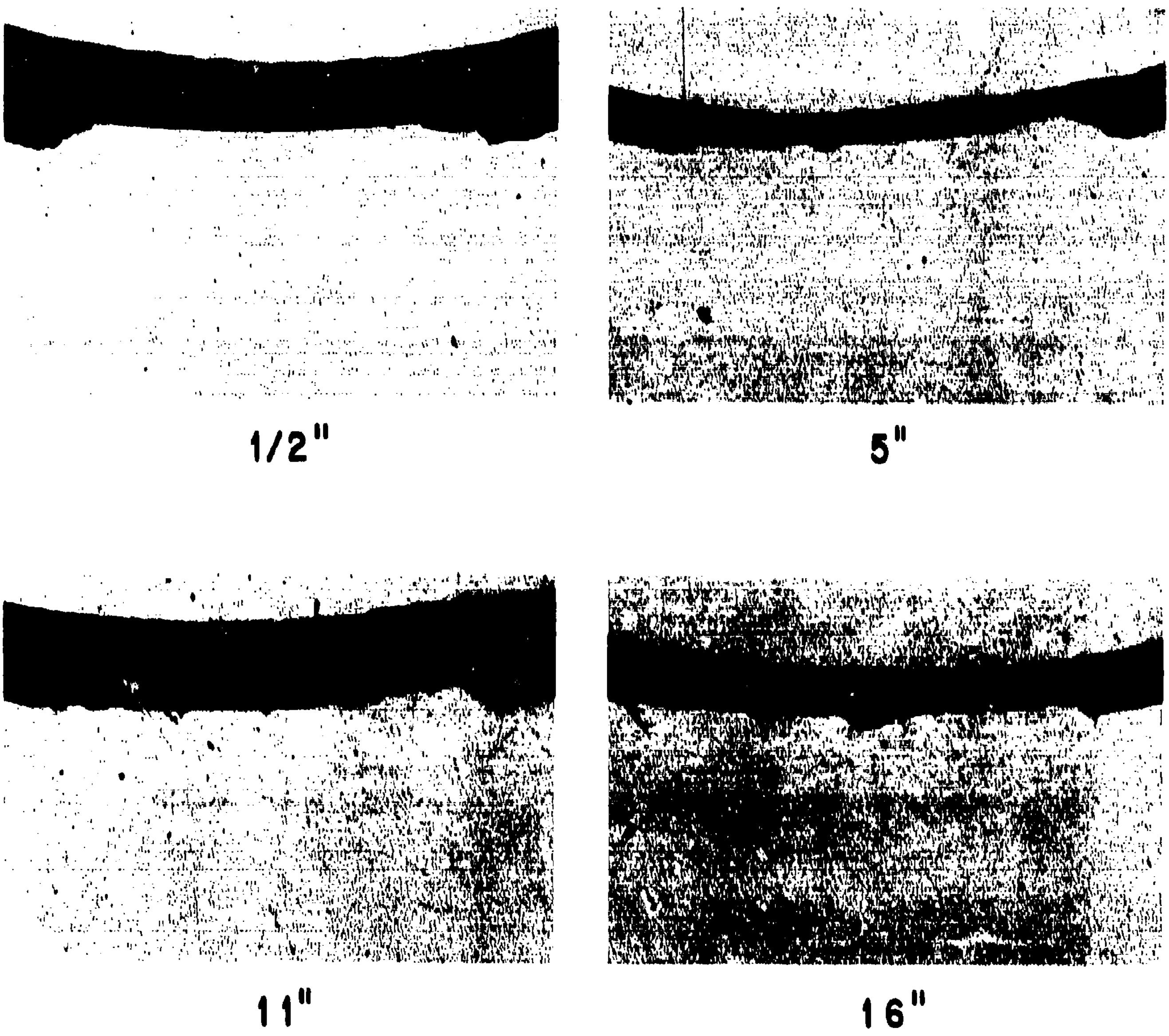


Figure 33 Photomicrographs of Lands from Tested Barrel 1483 (50X)

coating and lands, primarily on the leading edge. The muzzle end shows loss of entire lands, with retention of the coating in the grooves.

Comparison of these cross sections indicates that coating thickness is not the critical factor in barrel life, since little evidence of coating wear is observed; loss or retention of the coating appears to be the significant factor.

A more critical examination of the barrel substrate hardness was conducted. Figure 34 shows the effect of a 1250°F temper on the hardness of pieces of barrel chamber material from both a low temperature and a high temperature coated barrel. This temperature was chosen to approximate the barrel ID temperatures reached during testing. It can be seen that the low temperature coated substrate was initially somewhat softer than desired, and it continued to soften with time. Although the high temperature barrel softened, it still retained acceptable hardness after four hours at 1250°F. Figure 35 gives the hardness measurements for a low temperature coated and tested barrel cross section traversing from the barrel OD to the barrel ID. The hardness readings were taken with a Knoop Microhardness Tester and converted to Rockwell C. All the readings are below those of a standard chromium barrel, but it can be seen that the hardness drops rapidly approaching the ID, with the final reading being R_C8.

These data indicate that although the low temperature coated barrels were post-coating tempered to R_C30, the final substrate structure was unacceptable for testing. This substrate apparently softened under testing conditions. Such a soft base material would deform during testing, causing cracks in the coating and, in severe cases, coating loss. Thermal and chemical erosion would then occur at these points to undermine the coating and cause coating loss over large areas. Barrel lifetime would then be expected to be even less than normal for the remaining unprotected substrate due to its improper structure.

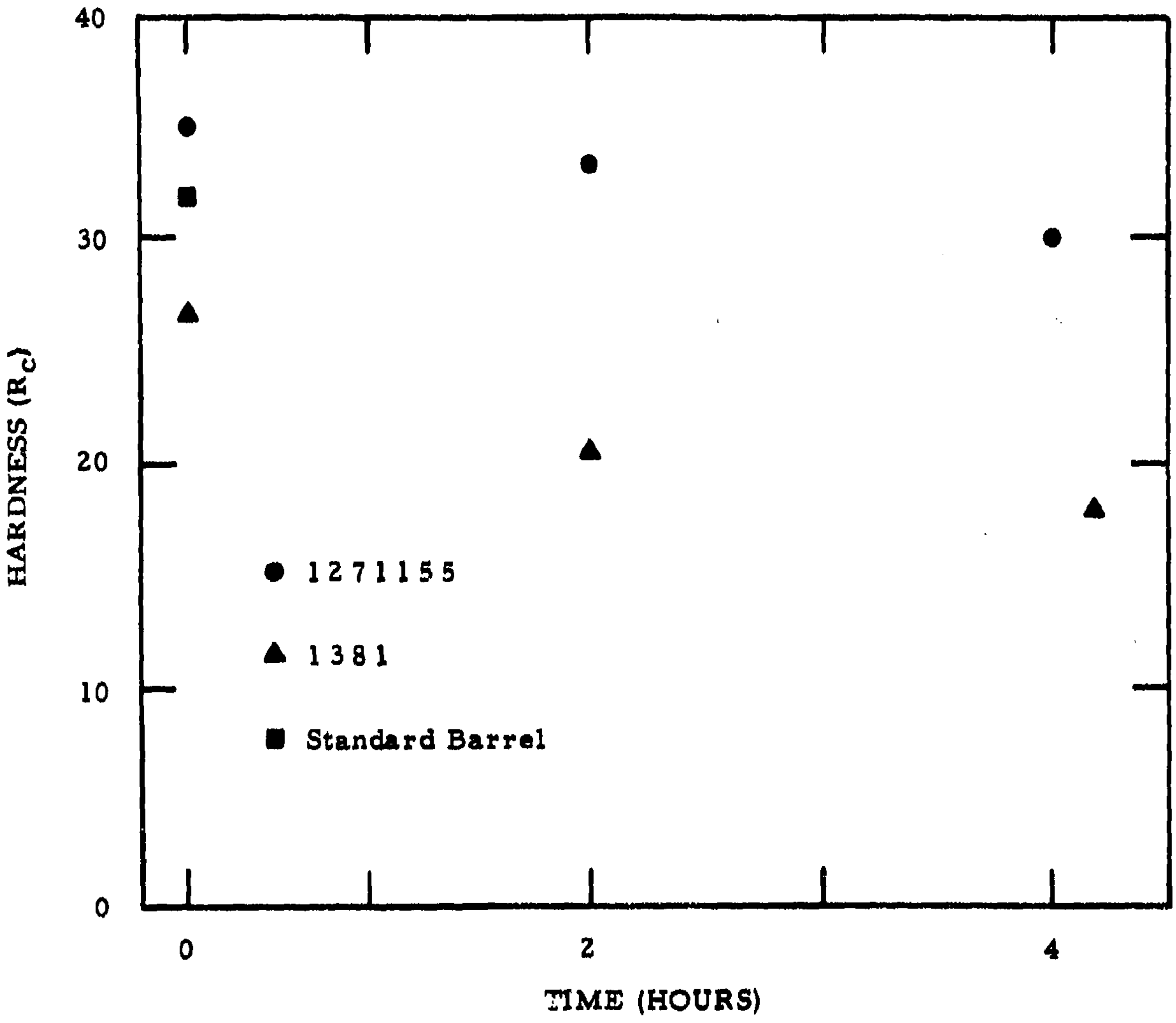


Figure 34 Effect of Tempering at 1250°F on Hardness of Gun Barrels, 1381 - low temperature process, 1271155 - high temperature process

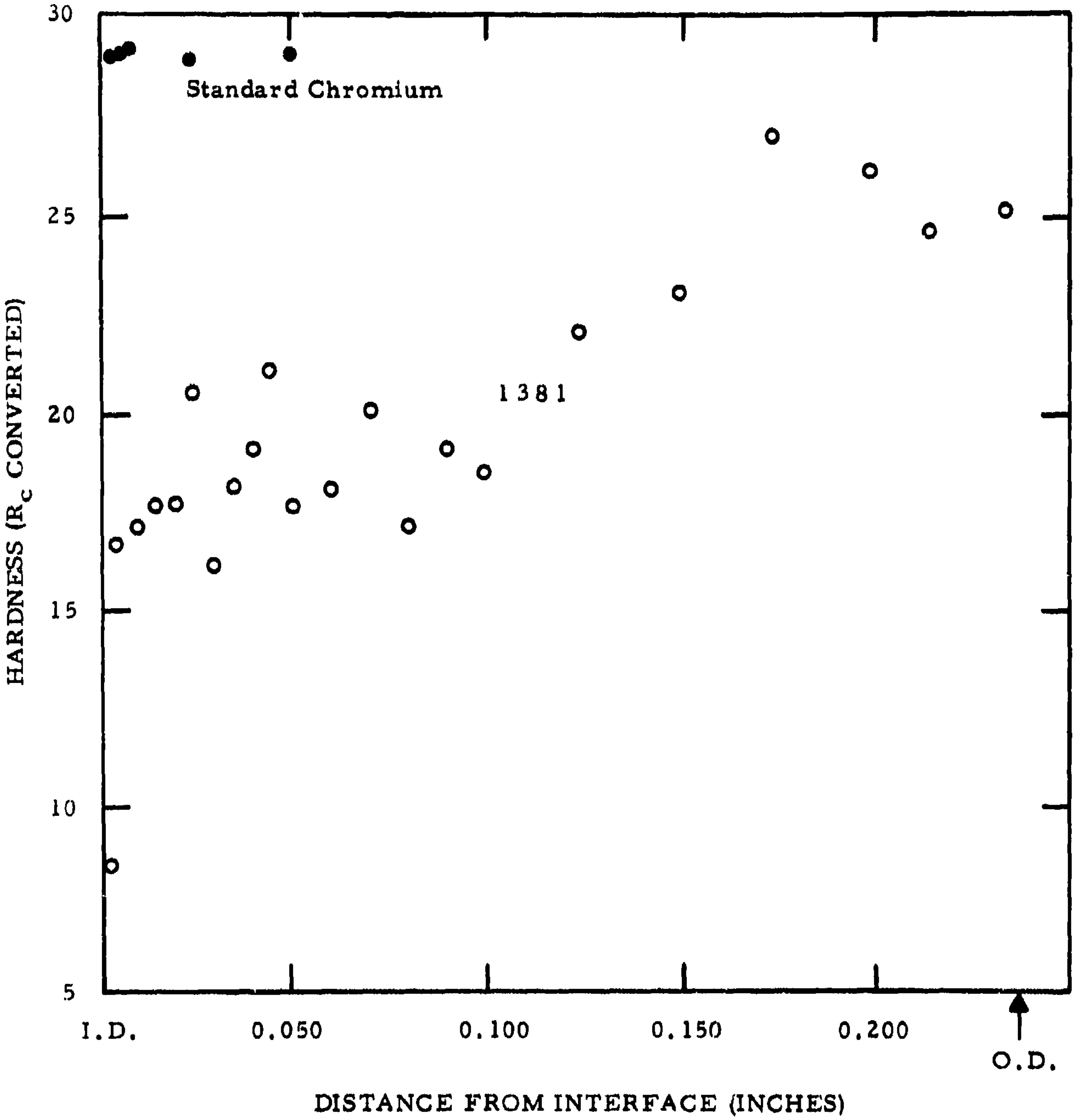


Figure 35 Hardness Traverse From ID of Steel In Fired Barrels

The third set of coated 7.62 mm machine gun barrels was shipped to the Naval Weapons Laboratory and then to Rock Island Arsenal. The set consisted of:

Barrel No. 5160	"1 mil" coating, high temperature process
Barrel No. 5161	"1 mil" coating, high temperature process
Barrel No. 5169	"3/4 mil" coating, high temperature process
Barrel No. 5173	"3/4 mil" coating, high temperature process

Substrate hardness was R_C30-33, measured on the outer surface of the breech end and on the holding flanges. Appearance of the coating, viewed down the barrel, was good: virtually chip free, with only an occasional nodule. Figure 34 indicates this third set of barrels should better retain its substrate hardness under the test conditions and, consequently, should show better performance than the previous low temperature barrels.

SECTION V
CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

1. The application of very controllable, uniform titanium carbonitride coatings of high quality appearance was demonstrated by two reliable processes.
2. Adhesion of the coating was very good from both processes, even through severe bending of the substrate occurred.
3. No particular advantage was noted for either process; though the high temperature process seemed to require less precleaning, the low temperature process appeared to give a smoother coating.
4. Economic projections from the very crude base point of laboratory-scale operation suggest low production costs once equipment has been developed sufficiently to obtain reasonable results for the labor expended.
5. To produce a component having the correct final ID, careful consideration must be given to all processes [cleaning, metal stripping (if any), and polishing] preceding the coating.
6. Land geometry is important for best performance, and manufacturing techniques must be incorporated to provide the desired final land shape and height; the "as-machined" lands often have burrs and sharp corners.
7. The test firing data do not indicate any difference in the performance of different thicknesses of coating in the low temperature coated barrels.
8. Examination of the barrels subjected to test firing at the Naval Weapons Laboratory showed failure mechanisms were apparently similar to those for chromium-plated barrels. Cracks apparent in the coating could permit gas embrittlement of the steel, particularly at the base of the lands in the chamber section.
9. The coating generally appears to be quite stable in the chemical environment and was not obviously degraded (except for fractures), which validates the usefulness of the coating as a liner.
10. The suspected cause of failure was deterioration of the steel substrate. Tempering at 1250°F caused extreme softening and the soft (to R_C8) substrate condition of the barrels after firing.

B. Recommendations

1. It is recommended that the test firing be completed, the fired barrels examined, and data on the failure modes analyzed.
2. Application of this coating to barrel substrate materials having high temperature capabilities, such as Udimet 700 or TZM, could provide a step function improvement in weapon life or performance.
3. The technology for application of a coating with controlled thickness is available, and alternate materials should be considered as liners for use with high potential substrates.

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13. ABSTRACT

This program was undertaken to contribute to improvement in the life of rapid fire machine gun barrels by manufacturing composite barrels by lining steel barrels with a refractory carbide material. The liner was applied by chemical vapor deposition of the coating on the barrel inside diameter. Two systems, low and high temperature, were used for the depositions. Both yielded high quality titanium carbonitride liners which had good adherence and controlled thickness. Controlled firing tests showed that the performance of barrels lined by the low temperature method was less satisfactory than that of standard chromium plated barrels. Post-firing analysis indicated that the substrate metallurgical condition allowed the steel to soften at operational temperatures and caused early failure of the barrels. The liner itself appeared relatively unchanged during the tests. The performance of barrels lined by the higher temperature method was comparable to that of standard barrels. It was concluded that although the titanium carbonitride liner material offered surface protection, base materials with improved high temperature capability will also be required to achieve longer lifetimes for barrels.

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